AD NUMBER

AD880561

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to DoD only; Administrative/Operational Use; JAN 1971. Other requests shall be referred to Air ForceAero Propulsion Lab., AFSC, Wright-Patterson AFB, OH 45433.

AUTHORITY

AFWAL ltr, 29 Feb 1984

V

AFAPL-TR-70-83

Volume I

AD-880561

AIRCRAFT FUEL TANK INERTING PROGRAM

Volume 1, Data

MacKenzie L. Hamilton

AiResearch Manufacturing Company
Los Angeles, California

TECHNICAL REPORT AFAPL-TR-70-83, VOLUME I

January 1971

Air Force Aero Propulsion Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

[redacted]

The distribution of this report is limited because the B-I and a tactical fighter-type aircraft (TFA) data included in the report should have only limited distribution.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIRCRAFT FUEL TANK INERTING PROGRAM

Volume 1, Data

MacKenzie L. Hamilton

AiResearch Manufacturing Company
Los Angeles, California

FOREWORD

The Aircraft Fuel Tank Inerting Program was conducted by AiResearch Manufacturing Company, a division of The Garrett Corporation, under USAF Contract No. F33615-70-C-1492. This work was sponsored and administered under the direction of the Aero Propulsion Laboratory under Air Force Project 3048, Task 304807. Mr. Steven D. Shook, AFAPL/SFH, was the Project Engineer for the Air Force.

The work was conducted from 1 April 1970 through 31 October 1970. MacKenzie L. Hamilton was responsible for the program at AiResearch. Major contributions were made by Charles F. Albright, Colin F. McDonald, James C. Noe, and Te Fung Yeh.

This report was submitted on 6 November 1970 under AiResearch Report No. 70-6926. Volume I contains the bulk of the report and Volume II (SECRET) contains inerting system specifications for the B-1 and a tactical fighter-type aircraft (TFA).

Volume II of this report contains classified information extracted from data obtained by Mr. Shook and transmitted to AiResearch. The data transmittals are 70AP-356 ("(U) Typical Bomber Flight Profile and System Performance for the Study and Design of a Catalytic Inerting System"), 70ASX-580 ("(U) TFA Performance Data for Contract F33615-70-C-1492"), and AFAPL/APFH-112 ("(U) Additional Performance Data on the TFA Aircraft, etc.").

This technical report has been reviewed and is approved.

Benito Botteri
Chief, Fire Protection Branch
Fuels and Lubrication Division
Air Force Aero Propulsion Laboratory

ABSTRACT

The Aircraft Fuel Tank Inerting Program has compared inerting system concepts and performed a preliminary design of the preferred inert gas generator (IGG) system for the B-l aircraft. Inerting system specifications have been developed for the B-l and a tactical fighter-type aircraft (TFA). The preliminary design activity has been supported by catalyst and catalytic reactor laboratory testing. With the exception of the catalytic reactor, the inerting system components are state of the art and similar in design and function to aircraft environmental control system (ECS) components. The program compared the IGG inerting concept with the liquid nitrogen inerting method of providing inert gas to the fuel tanks. The IGG concept appears to offer both weight and operational advantages (by eliminating the requirement for supply of cryogenic nitrogen). It uses aircraft engine fuel and bleed air as the inert gas source by catalytic reaction to remove the oxygen from the bleed air. Ram air and fuel are used as heat sinks for inert gas cooling and moisture removal. Low temperature moisture removal is provided by a cooling turbine (similar to those used for aircraft environmental control) to reduce the moisture content to levels below those obtained in service with fuel tanks vented to ambience.

PRECEDING PAGE BLANK-NOT FILMED

CONTENTS

Section		Page
I	INTRODUCTION AND SUMMARY	1
	General	1
	Summary of Results	2
	Recommendations for Future Activities	6
II	COMPARISON AND SELECTION OF INERTING CONCEPTS	9
	Introduction	9
	Inert Gas Source Concepts	9
	Gas Cooling and Moisture Removal Concepts	27
	Supplemental Moisture Removal	46
	System Synthesis and Selection	53
III	BASELINE LIQUID NITROGEN INERTING SYSTEM PRELIMINARY DESIGN	67
	Introduction	67
	Quantity of Nitrogen Required for Inerting	67
	System Configuration	69
IV	INERT GAS GENERATOR INERTING SYSTEM PRELIMINARY DESIGN	73
	Introduction	73
	System Schematic Description	74
	System Operation and Control Techniques	79
	System Performance Summary	79
	Component Performance Data	88
V	CATALYST AND CATALYTIC REACTOR TESTING	97
	Introduction	97
	Test Equipment	98
	Catalyst Studies	102
	Heat Transfer Studies	115

ILLUSTRATIONS

Figure		Page
1	Inerting Process Functional Block Diagram	3
2	Selected Inert Gas Generator Simplified Schematic	5
3	Catalytic Reactor Test Unit	7
4	Catalytic Reactor Fuel Flow and Heat Load	12
5	Surface Compactness Spectrum	14
6	Typical High Temperature Heat Exchanger Surface Geometries	14
7	Typical Plate-Fin Surface Geometries	16
8	Possible Heat Dissipation Variation with Flow	19
9	Catalytic Reactor Configuration	19
10	Simplified Schematic of a Single-Stage Combustor	21
11	Bootstrap Combustor/Reactor Schematic	22
12	Bootstrap Combustor/Reactor Performance	22
13	Nitrogen Separation from Air by Adsorption	24
14	Nitrogen Enrichment by Adsorption	24
15	Nitrogen Separation from Air by Absorption	26
16	Outlet Moisture vs Heat Sink Temperature	30
17	Possible ECS-IGG Integration	31
18	Ram Air Temperature vs Aircraft Altitude on MIL-STD-210A Hot Day	32
19	Possible IGG Vapor Cycle Refrigeration System	34
20	Basic Vapor Cycle Performance	35
21	Compound Freon/Air Cycle	35

ILLUSTRATIONS (Continued)

Figure		Page
22	Freon Cycle with Reduced Ram Air Flow	36
23	Dry-Air-Rated Performance of Simple and Bootstrap Cycles	37
24	Outlet Temperature and Moisture Content vs Inlet Pressure for Selected Simple and Bootstrap Cycle Concepts - Assumptions per Table 5	40
25	Regenerator Concepts	41
26	Direct Cooling Concepts	43
27	Vapor Cycle Concepts	43
28	Simple Cycle Cooling Concepts	43
29	Bootstrap Cycle Cooling Concepts	43
30	Sorbent Characteristics Comparison	49
31	Silica Gel Water-Loading Data	50
32	13-X Molecular Sieve Water-Loading Data	50
33	Direct Flow Bed Sorbent Weight	51
34	Regenerable Sorbent Bed Schematic	52
35	Regenerable Sorbent Bed Weight	53
36	Ram Air-Cooled Catalytic Reactor Weight	60
37	Vapor Cycle Heat Transfer Surface Weight	61/62
38	Vapor Cycle Rotating Equipment Weight	61/62
39	Inert/Ram Air Precooler Weight	61/62
40	Inert/Ram Air Heat Exchanger Weight	61/62
41	Inert/Fuel Precooler Weight	61/62
42	Inert/Fuel Heat Exchanger Weight	61/62
43	Regenerator Weight for Simple Cycle	61/62

ILLUSTRATIONS (Continued)

Figure		Page
44	Regenerator Weight for Bootstrap Cycle	61/62
45	Air Cycle Rotating Equipment Weight	61/62
46	Turbofan and Water Separator Weight	61/62
47	Selected Inert Gas Generator Simplified Schematic	65/66
48	Determination of Inflow Required for Fuel Scrubbing	68
49	Inert Scrubbing Inflow vs Aircraft Altitude	68
50	Liquid Nitrogen Inerting System Schematic	70
51	Liquid Nitrogen Inerting System Storage Tank Components	70
52	Nitrogen Tank Weight vs Insulation Thickness	72
53	Preliminary Design Logic Diagram	73
54	Inert Gas Generator System Detailed Schematic	75
55	Inert Gas Generator Packaging Configuration (AiResearch Drawing SK60110)	77/78
56	Analog Function for Flow Override and Fault Display/Shutdown	81
57	Typical High Bypass Engine Bleed Data	83
58	Inerting System Outlet Moisture Content for Ground Operation	86
59	Inerting System Outlet Moisture Content vs Flow Rate at 5000-ft Altitude	86
60	Inerting System Outlet Moisture Content Insensitivity to Ambient Humidity	86
61	Inerting System Outlet Moisture Content vs Mach Number at 5000-ft Altitude	87
62	Inerting System Outlet/Moisture Content at High Altitude Flight	89

ILLUSTRATIONS (Continued)

Figure		Page
63	Catalytic Reactor Performance Maps	90
64	Inert/Ram Air Precooler Performance Maps	91
65	Inert/Fuel Precooler Performance Maps	92
66	Regenerator Performance Maps	93
67	Turbine Performance Maps	94
68	Fan Performance Maps	95/96
69	Possible Methods Which May be Employed for Catalyst Light-Off	99
70	Performance with Catalytic Reactor Within Bootstrap Cycle (Aircraft at Mach 0.7, Sea Level, Hot Day)	100
71	Boot Compressor Airflow Requirements and Reactor Inlet Temperature	100
72	Catalytic Reactor Tube Bundle Schematic	101
73	Catalytic Reactor re Bundle Photograph	101
74	Catalytic Reactor Test Equipment Schematic	103
75	Catalytic Reactor Test Equipment Photograph	104
76	Tube Wall Temperature Variation for Typical American Cyanamid Code A Catalyst	109
77	Catalytic Reactor Tube Temperature Profiles	113
78	Catalyst Pressure Drop Data	114
79	Catalytic Reactor Tube Temperature Profiles	115
80	Recommended Catalyst Heat Transfer Data	118

TABLES

Table		Page
1	Inerting System Design Objectives	3
2	Inert Gas Generator System Performance Summary	5
3	Catalytic Reactor Test Summary	7
4	Inerting System Functional Concepts	10
5	Assumptions for Figure 24	38
6	Cycle Performance Comparison	44
7	Analysis Assumptions at IGG Design Point	44
8	Sorbent Characteristics	48
9	Cooling and Moisture Removal Concept Quantitative Data	58
10	Inerting Concept Weight Summary for TFA Aircraft	59
11	Inerting Concept Weight Summary for B-1 Aircraft	59
12	Selected Component Reliability Data	63
13	Cooling and Moisture Removal Concept Evaluation Matrix	64
14	Nitrogen Quantities Required For B-1	69
15	Liquid Nitrogen Inerting System Weight	72
16	Inert Gas Generator System Weight	76
17	Primary Inerting System Operational Requirements	80
18	Primary Inerting System Control Requirements	80
19	Additional Inerting System Control Requirements	81
20	Inerting System Start Up/Shutdown Sequencing	83
21	Engine Bleed Air Pressures Assumed for Performance Analysis	83

TABLES (Continued)

Table		Page
22	Range of Aircraft Operating Conditions Used for Performance Analysis	84
23	Typical Integrated Mission Moisture Content	89
24	Typical Inerting System State Points	In Vol. II
25	Oxidation Catalysts Tested in Catalytic Reactor Test Unit	105
26	Platinum Catalyst Exhaust Gas Analysis: Sample 1	111
27	Platinum Catalyst Exhaust Gas Analysis: Sample 5	111
28	Code A Catalyst Exhaust Gas Analysis: Sample 1	112
29	Code A Catalyst Exhaust Gas Analysis: Sample 2	112
30	Inert Gas Catalytic Reactor Test Data Summary	116

SECTION I

INTRODUCTION AND SUMMARY

GENERAL

This report presents the findings of the Aircraft Fuel Tank Inerting Program performed by AiResearch under Contract F33615-70-C-1492 for the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio. The major study objectives are the following:

- Develop fuel tank inerting system specifications for a tactical fighter-type aircraft (TFA) and B-1 aircraft
- Synthesize a number of candidate systems that use a catalytic reactor as the inerting gas source and compare them with a baseline concept using liquid nitrogen as the inert gas source
- Perform preliminary design of the reactor system concept best satisfying the specific B-1 performance requirements
- Establish state of the art in the recommended design concepts and suggest future technology improvements

Scope of Study

This study was approximately six months in duration and represents a 1.5 man-year effort. In addition to performing the activities required to accomplish the above objectives, the study has also devoted considerable effort to testing of candidate catalysts and determination of catalytic reactor heat transfer data. This testing was necessary to provide data for preliminary design of the selected inerting system.

The study activities are presented as follows in this report:

Section II	Comparison and Selection of Inerting Concepts
Section III	Baseline Liquid Nitrogen Inerting System Preliminary Design
Section IV	Inert Gas Generator Inerting System Preliminary Design
Section V	Catalyst and Catalytic Reactor Testing
Appendix A	(SECRET) B-1 Inerting System Specification
Appendix B	(SECRET) TFA Inerting System Specification

System Performance Requirements

The primary performance requirements for the inerting systems are shown in Table I. The system flow rates are established by the aircraft fuel tank volumes and maximum normal descent and emergency descent capabilities. In the case of the TFA aircraft, the normal descent and emergency descent capabilities are identical since this aircraft is designed for rapid inflight combat maneuvers.

Both the allowable oxygen content and moisture content have a significant effect on the overall system weight and configuration. The oxygen content was selected to maintain the fuel tank ullage space at less than 9-percent oxygen by volume. An oxygen content of less than about 11 to 12 percent in the tanks is essential if inerting is to be accomplished. A nominal maximum inerting system gas oxygen content of about 5 percent is required if the inert inflow during initial aircraft climb (when dissolved oxygen evolves from the fuel) is to be less than the flows required during aircraft descent. Similarly, the moisture content was selected to provide a maximum gas moisture content approximately equivalent to that obtained on the ground on a hot, humid day. Additionally, the integrated mission average design objective of 25 grains water/lb of inert gas was selected since this value is somewhat below the average moisture content resulting from descent to sea level on a hot, humid day with fuel tanks vented to ambience.

SUMMARY OF RESULTS

Inerting System Specifications

Specifications for inerting systems for the B-1 and TFA aircraft are presented as Appendixes A and B of this report. These appendixes are bound separately to meet classification requirements. They detail the system operational functions during each aircraft flight mode and establish the performance requirements summarized in Table I.

Synthesis/Evaluation of Candidate Inerting System Concepts

Figure 1 shows the three functional elements of an inerting system and the concepts evaluated. The evaluative studies are presented in Section II of this report. These studies show that it is possible to provide a low moisture content in the inert flow to the fuel tanks without resorting to the supplemental moisture removal concepts such as desiccant beds and water separators. Furthermore, the air-cycle refrigeration techniques conventionally used on both commercial and military aircraft are the optimum cooling/moisture removal techniques for the inerting application as well.

The simple air-cycle refrigeration system shows a slight overall advantage over the bootstrap air-cycle systems. This evaluation is based on a comparison process that assigns weighting factors to the relative ratings for each candidate concept's weight, performance, reliability, maintainability, and cost. The bootstrap cycle, however, potentially can provide a lower moisture content than can the simple cycle system. Thus, for applications requiring

TABLE I

INERTING SYSTEM DESIGN OBJECTIVES

Parameter	Value	Basis for Selection
Flow rate	• B-1 67 lb/min maximum normal inflow 200 lb/min maximum during emergency descent • TFA: 20 lb/min maximum normal inflow	• Aircraft with empty fuel tanks at maximum descent rate at sea level
Gas oxygen content	• 2.5 percent volume oxygen nominal, 5 percent volume oxygen maximum normal • 7.5 to 10 percent volume oxygen during B-1 emergency descent	• Avoid ever operating fuel-rich since fuel carryover would degrade heat transfer and cooling equipment • Provide low enough oxygen content to maintain tanks inert during initial air-climb when oxygen evolves from fuel
Gas temperature	• 32° to 200°F normal operation • 32° to 325°F during emergency descent	• Avoid freezing at all locations within system • Minimize heat input to fuel
Gas moisture content	• 80 grains/water lb inert maximum normal inflow • 25 grains water/lb inert maximum integrated mission average	• Introduce less water into fuel tanks than would occur with unpressurized tanks vented to ambience

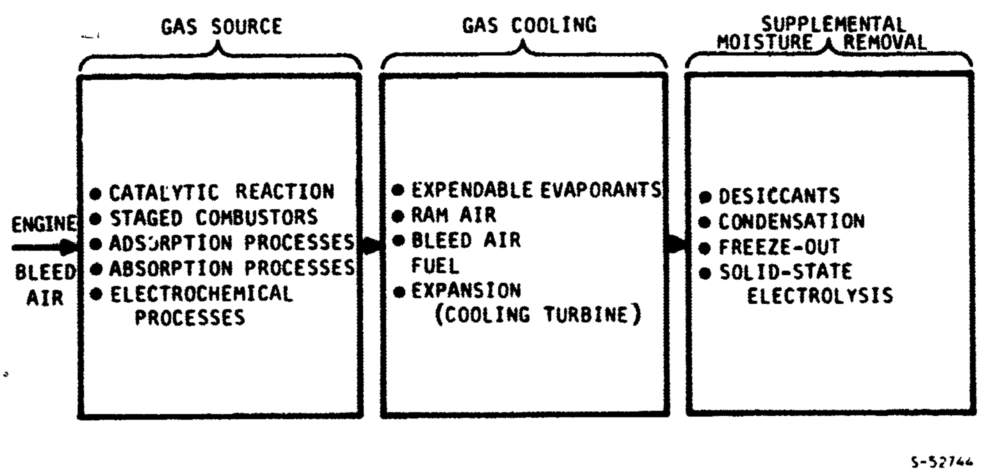


Figure 1. Inerting Process Functional Block Diagram

an extremely low moisture content (it should be noted that the selected system concept provides an integrated output moisture content of only 5 grains water/lb inert), the bootstrap configuration might be preferable.

Baseline Liquid Nitrogen Inerting System Preliminary Design

The liquid nitrogen inerting system has been used as the baseline against which the inert gas generator system was compared. Almost all of the liquid nitrogen inerting system weight is dependent upon the total quantity of inert gas to be delivered to the fuel tanks. For the B-1, the analyses in Appendix A and those presented in Section III, indicate that 450 to 900 lb of liquid nitrogen will be required. The 900-lb quantity assumes that only pure nitrogen is input to the tanks and that the fuel is loaded into the tanks in bulk form. The 450-lb quantity assumes that bleed air is mixed with the nitrogen to provide the inert flow to the tanks and that the fuel is loaded into the tanks by spraying it into the inert atmosphere.

The total fixed weight of the liquid nitrogen inerting system (exclusive of distribution lines and valving on the fuel tanks) will be no more than 11 percent of the deliverable quantity of liquid nitrogen.

Inert Gas Generator Inerting System Preliminary Design

1. System Description

Figure 2 shows a simplified schematic of the inerting system concept selected for preliminary design. This concept uses a ram air cooled catalytic reactor as the inert gas source. Gas cooling and moisture removal is accomplished by a simple air cycle refrigeration system. The hot inert flow from the catalytic reactor is cooled in an inert/ram air precooler and can be additionally cooled in the inert/fuel precooler during high speed flight when ram air alone does not provide adequate cooling. After this preliminary cooling process, the inert flow passes through a regenerator that uses the cold inert discharged from the cooling turbine as its heat sink. From the regenerator, the inert expands across the turbine and passes through the regenerator prior to being distributed into the fuel tanks. The regenerator performance is enhanced by using a jet pump on the turbine discharge flow to recirculate a portion of the inert gas. This increases the cold-side mass flow in the regenerator, improving its overall performance and eliminating the possibility of freezing at the turbine discharge. Without this recirculation loop, the temperature of the inert flowing into the cold side of the regenerator would be well below $0^{o}F$.

2. System Performance

Table 2 summarizes the system performance data presented in Section III. The system meets or exceeds the intent of all design objectives listed in Table I. In comparison to the liquid nitrogen inerting system, the inert gas generator shows a potential weight advantage, and it has decided operational advantages. The IGG system requires none of the ground servicing equipment essential to operation of the liquid nitrogen inerting system. Additionally,

TABLE 2

INERT GAS GENERATOR SYSTEM PERFORMANCE SUMMARY

Flow Rate	
Normal flight operations	6 to 67 lb/min
Emergency descent	6 to 200 lb/min
Inert Gas Properties	
Normal output oxygen content	2.5 ±2.5 percent
Emergency descent gas oxygen content	7.5 ±7.5 percent
Normal gas temperature	69° to 158°F
Emergency descent gas temperature	About 320°F at maximum flow
Normal flight moisture content	See Figures 59 to 65 of Section III
Typical integrated mission moisture content	5 gr/lb inert generated 8 to 12 gr/lb inert input to fuel tanks
Fuel, Ram Air, and Bleed Air Usage	
Catalytic reactor fuel flow	0.0595 lb fuel/lb bleed air
Bleed air flow	1.025 to 1.044 lb bleed air/lb inert output, depending upon ambient humidity
Ram air flow	4.9 to 6.2 lb ram air/lb bleed air, depending upon aircraft flight speed and altitude, and upon ambient temperature and humidity
Total equivalent fuel penalty	About 0.08 lb fuel/lb inert

System Weight	
Catalytic reactor	88 lb
Heat exchangers (3 total)	488 lb
Air cycle machine	28 lb
Control components	50.5 lb
Other, miscellaneous	45.5 lb
Total weight	700 lb
System Servicing and Maintenance	
Ground support equipment	Identical to aircraft ECS support equipment
Flight line servicing equipment	None required
Maintenance intervals	Estimated at 500 flight hours minimum

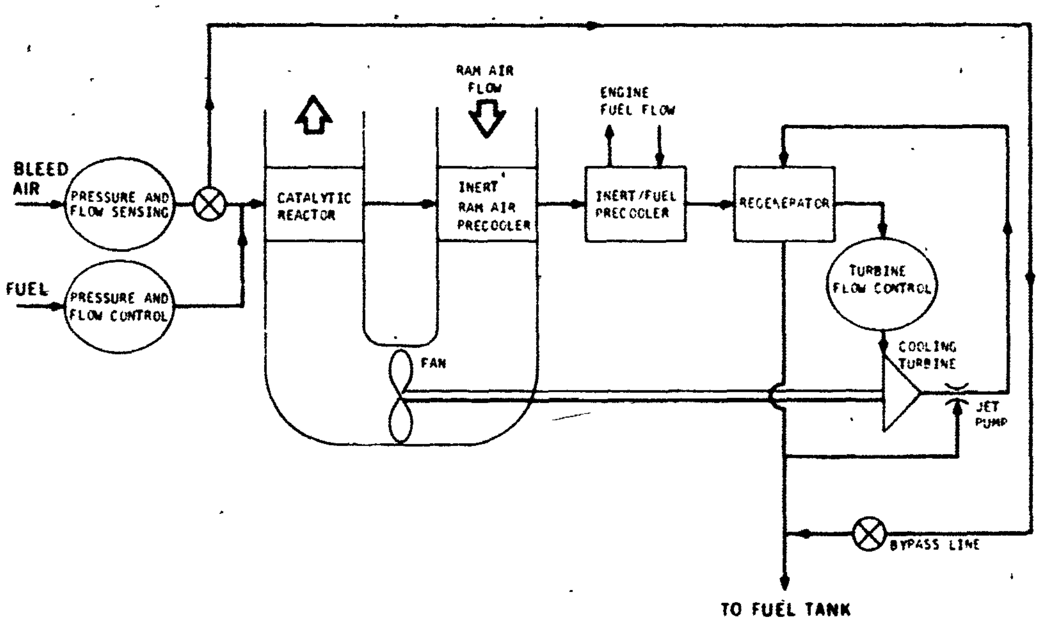


Figure 2. Selected Inert Gas Generator Simplified Schematic

the IGG system can provide an unlimited quantity of inert gas, being limited only by the availability of aircraft fuel and bleed air. Thus, the IGG concept becomes particularly attractive for an aircraft that may remain airborne for extended periods or that may operate from widely-separated or dispersed bases.

Catalyst and Catalytic Reactor Testing

Section V of this report presents the test data obtained on candidate catalysts for the catalytic reactor. Additionally, it presents heat transfer data that may be used to size the reactor. Figure 3 shows a photograph of the catalytic reactor test unit. It is constructed of stainless steel tubing with provisions for air to be blown across the tubes to provide cooling. The high pressure air and fuel are mixed in a chamber upstream of the reactor and distributed via the inlet manifold to the individual tubes. Selected tubes were instrumented at intervals along their length to provide data on the tubing temperatures. Additional instrumentation was used to measure the inlet fuel/air ratio, pressure, and temperature, the cooling airflow, and the reactor discharge pressure, temperature, and gas composition.

Table 3 summarizes the major findings of the reactor tests.

RECOMMENDATIONS FOR FUTURE ACTIVITIES

This study has shown that a catalytic reactor inert gas generator system shows potential benefits over other methods of providing fuel tank inerting for large aircraft. Therefore, it is recommended that this type of inerting system be developed and laboratory tested. The testing will be oriented toward establishing the performance potential predicted by the analytical techniques presented in this report. Because of the similarity between the selected inert gas generator concept and aircraft environmental control systems, many of the inerting system components could be made av ilable for the test program as off-the-shelf hardware items.

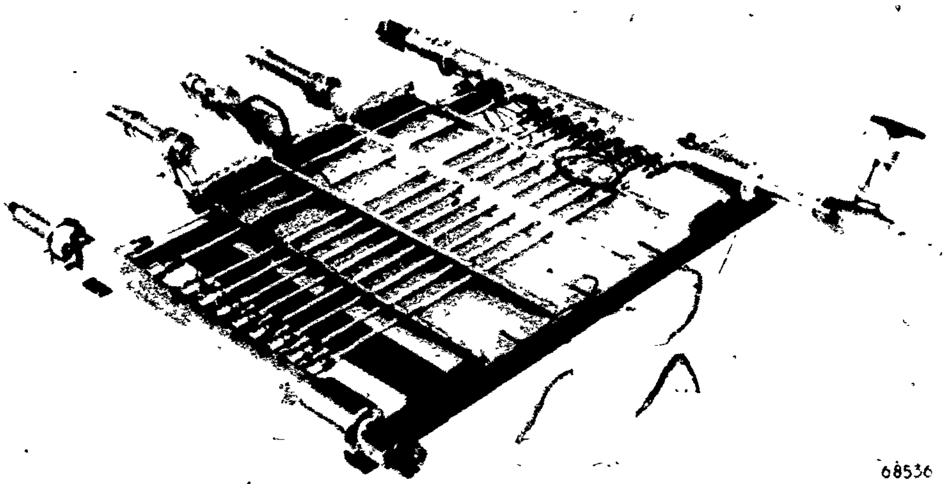
A second recommended future effort is the development of oxygen sensors capable of operating in an aircraft environment, and specifically, of operating in the moisture- and fuel-laden atmosphere potentially present at various points in the inerting system. Such sensors would allow the inerting system performance to be monitored and would greatly facilitate fault isolation within the system.

It should be noted that open-loop control concepts appear to provide more accurate control of the fuel/air ratio into the catalytic reactor than that obtainable even with future technology oxygen sensors. Thus, the inerting system performance is not dependent upon oxygen sensor development, but it would be enhanced by such development.

TABLE 3

CATALYTIC REACTOR TEST SUMMARY

Number of catalysts tested	38
Catalyst types showing applicability	Precious metals: platinum and palladium Metal oxides: oxides of copper, manganese, and silver
Recommended catalyst arrangement	American Cyanamid Code A catalyst or Grace 908 catalyst (alternate), intermixed with platinum with an initial igniter length of platinum catalyst
Recommended catalyst carrier	Alumina pellets about 0.1 in. diameter to provide low pressure drop and good flow turbulence
Minimum catalyst ignition temperature	400° to 450°F
Maximum tubing wall temperature	About 1250°F if conventional materials are to be used
Recommended tubing material	Type 347 stainless steel
Reactor discharge gas composition	Low nitrogen oxide count, low hydrocarbon count, initial condensate has pH of about 3.0



SECTION II

COMPARISON AND SELECTION OF INERTING CONCEPTS

INTRODUCTION

This section presents the study analyses and conclusions leading to selection of the preferred inerting system concept. First, the candidate concep~~ts for the~~ various system functions (inert gas source, gas cooling and moisture removal, and supplemental moisture removal) are analyzed to establish their performance potential. Then, a set of weighted evaluation criteria are used to select the optimum system configuration. The preliminary design of this selected concept is presented in Section IV.

Organization

The major divisions of this section are as follows:

- Inert gas source concepts
- Gas cooling and moisture removal concepts
- Supplemental moisture removal concepts
- System synthesis and selection

The first three divisions analyze the performance capabilities of each concept and summarize its applicability for the inerting system application. The last division combines these concepts that have been found to be applicable into a series of candidate inerting systems. From these systems, the 11 most promising configurations were selected for a detailed comparison with one another. A set of weighted evaluation criteria, consisting of performance, weight, reliability, maintainability, and cost are used to select the optimum fuel tank inerting system.

Summary of Selected System

The evaluation comparisons indicate that the optimum inerting system concept uses a ram air-cooled catalytic reactor as the inert gas source, with an air cycle refrigeration system being used to provide gas cooling and moisture control. The air cycle refrigeration unit consists of an inert/ram air precooler used during all flight modes, an inert/fuel precooler used only during high-speed supersonic flight (when the ram temperatures become excessively high for moisture removal by condensation), an expansion turbine loaded by a fan, and a regenerative heat exchanger (uses turbine exhaust gas to precool the inert flow prior to entering the turbine).

INERT GAS SOURCE CONCEPTS

The inert gas source preferentially removes oxygen from air to provide an output having less than 5 percent free oxygen by volume. There are other possible methods of providing an inert gas which are not dependent upon starting with air, such as carrying a supply of inert gas on the

TABLE 4

INERTING SYSTEM FUNCTIONAL CONCEPTS

Function	Concepts Considered
Inert Gas Source	Catalytic Reactor (in several different configurations) Combustor (single and staged Bootstrap Combustor/Reactor Cycle Oxygen Adsorption Processes Oxygen Absorption Processes Electrochemical Processes
Gas Cooling and Moisture Removal	Direct Cooling (2 different configurations) Vapor Cycle Refrigeration (5 different configurations Simple Air Cycle Refrigeration (6 different configurations Bootstrap Air Cycle Refrigeration (12 different configurations
Supplemental Moisture Removal	Water Coalescer/Separator Direct Flow Sorbent Beds (2 different materials Regenerable Sorbent Beds (2 different materials)

aircraft (liquid nitrogen, for example) or reacting chemicals to generate an inert gas (hydrazine decomposition, for example). The primary intent of this study, however, is to synthesize a catalytic reactor inerting system operating on air; additional oxygen removal concepts have been briefly considered to insure that the catalytic reactor method is the optimum.

The inert gas sources considered are as follows:

- Catalytic reaction of air and fuel
- Combustion of air and fuel
- Bootstrap combustor/reactor cycle operating on ram air
- Adsorption processes in which oxygen is preferentially adsorbed from the air onto the adsorbent surface (a physical process)

- Absorption processes in which oxygen is preferentially absorbed from the air into the absorbent material (a chemical process)

- Electrochemical processes in which oxygen dissolves in an electrolyte and passes from the anode to the cathode and into an oxygen-rich waste stream

It should be noted that, for turbine engine aircraft the turbine exhaust gas has an oxygen content varying between 18 to 20 percent by volume. Consequently, fuel tank inerting systems using turbine exhaust gas would also require an additional method of removing oxygen; thus, the integration of the inert gas source with the engine turbine air (either turbine inlet or exhaust) does not eliminate the necessity for a separate inert gas source. Therefore, only concepts operating with air at ambient composition have been considered.

The study indicates that only the catalytic reactor and the combustor are capable of providing inert gas at a reasonable weight and bleed air usage. Of these two, the catalytic reactor offers maintenance and performance advantages over the combustor. The reactor operates at lower temperatures and has no external power supply, such as would be required for the combustor.

The material below describes each of the candidate concepts, indicating their relative performance. It assumes that all concepts except the bootstrap combustor/reactor cycle are operated with bleed air rather than ram air. Ram air might be acceptable for some of the concepts during high speed flight when there is sufficient ram pressure; however, during other flight modes, particularly when the aircraft is on the ground, the ram pressure is insufficient. A similar situation occurs on aircraft environmental control systems where ram might be suitable during some flight modes, but is insuitable during others. Weight and reliability considerations for ECS's have led to systems that utilize bleed air during all flight modes. Similarly, it appears that bleed air will be the optimum process air source for the IGG. Ram air, as discussed later, will be used extensively as a heat sink for process gas cooling.

<u>Catalytic Reaction</u>

Catalytic reaction of fuel and air can be accomplished by passing the fuel/air mixture across a catalyst bed. The primary reactor design problem is the dissipation of the energy released by the exothermic reaction. Additional considerations of importance are the selection of the catalyst material and its degradation with time. Considerable previous work, however, has been devoted to investigation of catalysts (most notably the American Cyanamid study published as AFAPL-TR-69-68), and additional catalyst performance studies that have been conducted for this study are presented in Section V of this report.

The following material discusses the candidate reactor concepts, presenting the information as follows:

- Reactor heat load

- Potential heat sinks
- Candidate heat transfer surface geometries
- Flow configurations
- Material selection
- Ram air flow control
- Maintenance considerations
- Design summary

1. Reactor Heat Load

Typical reactor heat loads are shown in Figure 4. The equilibrium temperature of the inert gas due to this energy addition is about 4400°F, assuming inlet bleed air at 400°F for an outlet oxygen content on the order of 5 percent. Clearly, the reactor must be supplied with an integral heat sink if conventional materials are used. Additionally, it must operate over a large flow variation which will cause significant changes in the velocity of the fuel/air mixture as it passes across the catalyst bed; thus, the heat released within the bed along the bed length will be a function of the reactor flow rate. Therefore, the cooling supplied to the reactor must also be varied along the reactor length.

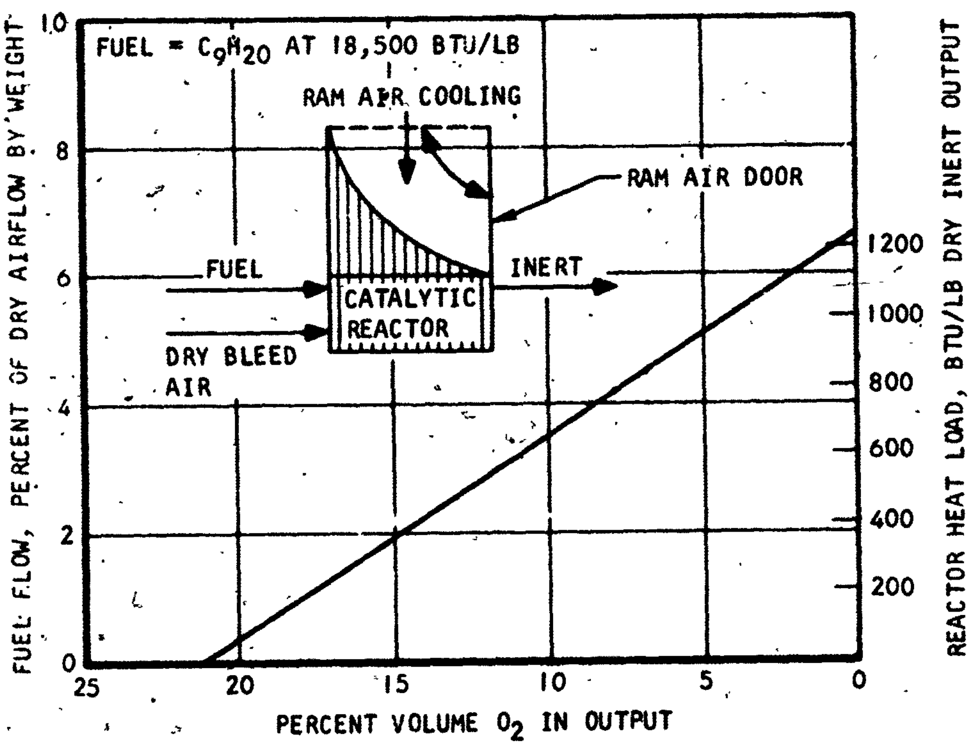


Figure 4. Catalytic Reactor Fuel Flow and Heat Load

2. Potential Heat Sinks

There are four heat sinks that could be used for the reactor:

- Ram air
- Engine fuel
- ECS-chilled air
- Water

Engine fuel has been eliminated as a candidate due to the potential safety hazard. Leakage of the cooling fuel into the reactor would greatly increase the heat generated within the reactor, possibly leading to destruction. ECS-chilled air could be used as a heat sink; however, the maximum flows through the reactor would necessitate a significant increase in the size of the ECS -- this concept is discussed further in the gas cooling and moisture removal information, but it does not appear optimum for military aircraft. Using water would require about 1 lb water per lb of inert; this represents an excessive weight penalty as well as requiring ground maintenance for periodic resupply of the water.

Thus, ram air has been selected as the reactor heat sink. The ram flow must be about 5 times the inert flow if the reactor temperatures are to be maintained within the limits of conventional materials.

3. Candidate Heat Transfer Surface Geometries

The reactor weight will consist primarily of the heat transfer surface required to dissipate the heat; only a minor portion will be the catalyst weight. Consequently, it is necessary to optimize the heat transfer surface, if the reactor weight is to be minimized. The following material considers three classes of heat transfer surfaces:

- Tubular surface geometry
- Finned tubular surface geometry
- Plate-fin surface geometry

The surface compactness relationship between these geometries is shown in Figure 5. It indicates a considerable overlap between geometries of different types. Typical high temperature heat exchanger surface geometries are shown in Figure 6.

a. Plain Tubular Surface Geometries

Preliminary analyses of possible tubular heat exchangers indicate that the heat transfer coefficient on the ram air side controls the size of the heat transfer surface. And since the heat transfer coefficient for flow

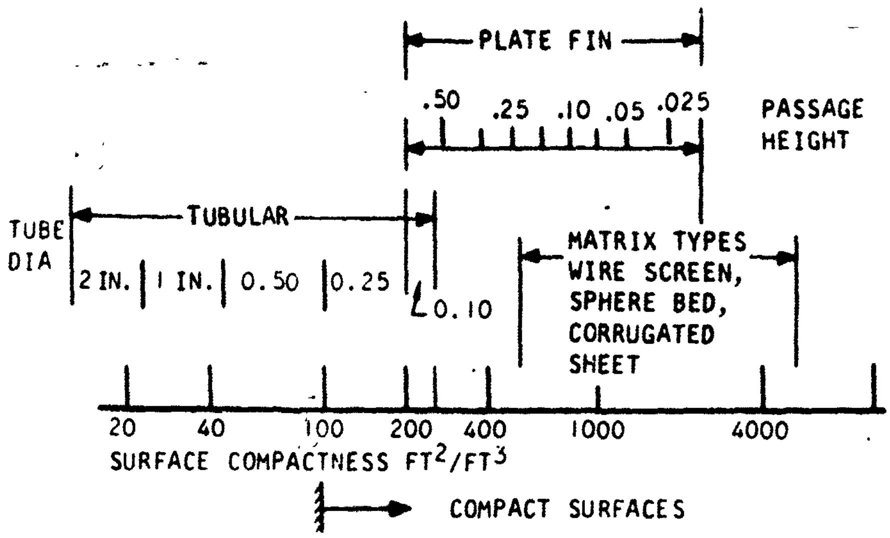


Figure 5. Surface Compactness Spectrum

S-59687

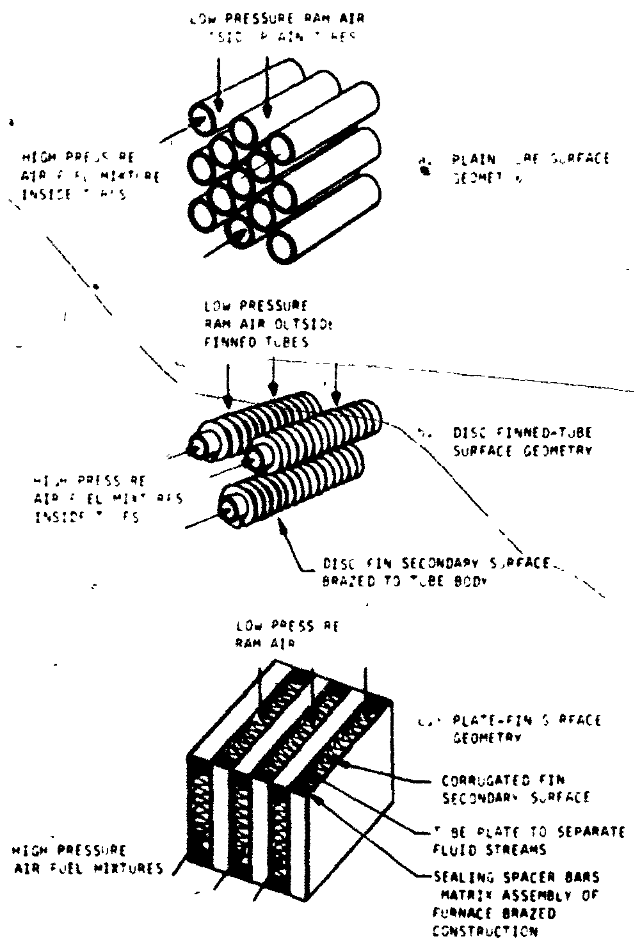


Figure 6. Typical High Temperature Heat Exchanger Surface Geometries

inside plain (nonturbulated) tubes is several times less than the coefficient for flow outside an otpimized tube bundle, the most desirable tube configuration would place the ram air on the outside of the tubes, where the flow coefficient is maximized.

Additionally the inner-side heat transfer coefficient can be significantly increased by turbulating the fluid flow. The best method of providing turbulence has been found to be ring-dimpling of the tubes at periodic intervals.

b. Finned Tubular Surface Geometries

With a gas-to-gas heat exchanger made from small diameter tubes, adding finned secondary surfaces on the outside of the tubes poses a serious, if not prohibitive, problem in fabricating dimples for inside-flow turbulation.

For designs with external secondary surfaces, the inside heat transfer coefficient can be increased by utilizing a plain strip, a wire spiral, or a flap turbulator inside the tube. With the plain strip brazed inside the tube, the hydraulic diameter is effectively reduced; this, together with the increase in heat transfer surface area, results in an improved internal conductance. Although the wire spiral and the flap turbulator are more effective heat transfer promotors, the associated increase in friction results in core sizes of large flow frontal areas and small flow lengths for units such as the catalytic reactor, where limited pressure loss is allowed.

c. Plate-Fin Surface Geometry

A number of secondary surfaces were evaluated, including plain triangular and rectangular offset fins of the type shown in Figure 7. In the majority of compact air cooled heat exchangers for aircraft and industrial applications, offset finned surfaces are utilized for minimum volume and weight. With such a surface, the fins are systematically pierced in the direction of flow and offset normal to the direction of flow as shown in Figure 7. This provides periodic interruption of the boundary layers and thereby increases the heat transfer coefficients. Boundary layer dissolution incurs a smaller pressure drop penalty than artificial turbulence promotion such as wavy, louvered, or herringbone fin configurations. Comparison of the various surface types indicates that compact offset rectangular fins result in matrixes of minimum volume, and thus represent an effective secondary surface.

d. Surface Selection

From the surface geometry comparison, a preliminary analysis has shown that the minimum weight counterflow plate-fin matrix weight, while lighter than the finned-tube variant, is much heavier than the dimpled plain tube design. With the main goal of the heat transfer analysis being to establish a surface geometry for minimum weight, a plain tube geometry has been selected for the reactor.

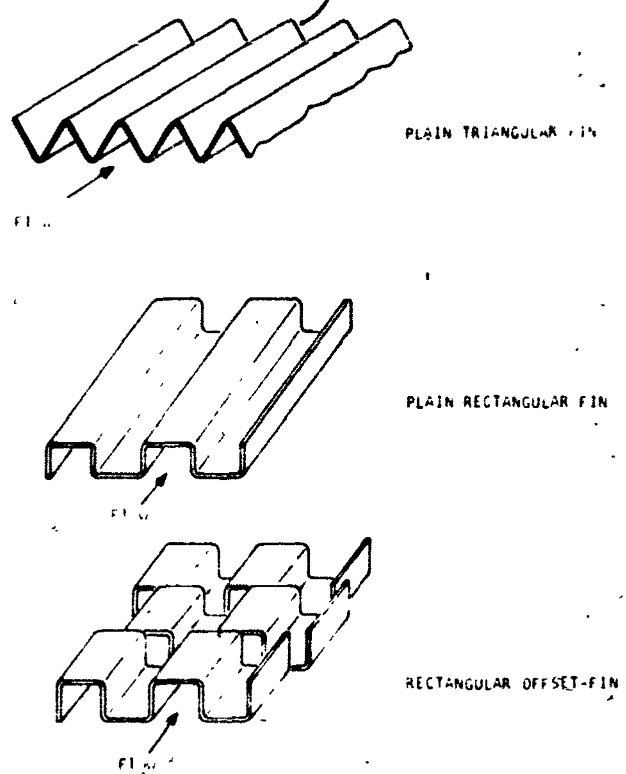


Figure 7. Typical Plate-Fin Surface Geometries

4. Flow Configurations

For a given heat load and thermal effectiveness, the minimum overall thermal conductance can be realized with a pure counterflow arrangement. For such an arrangement, end section headering areas are necessary to direct the hot and cold streams to and from the counterflow portion of the heat exchanger assembly. For the effectiveness desired for the catalytic reactor, including end sections would result in a weight penalty, so that simpler, lighter designs with cross flow or multipass cross-counterflow should be utilized. These configurations eliminate or reduce the weight associated with the headers.

a. Catalyst Outside the Tubes

Placing the catalyst outside the tubes limits the low-pressure ram air velocity because of the low pressure loss allowable on the ram side. Thus, with a design ram air pressure loss on the order of only 1 psia, the full advantage of tube ring dimpling cannot be realized and fairly low internal heat transfer coefficients exist. Also, because of the low ram pressure drop, only a single pass arrangement on the tube side can be considered. For such a configuration designed for 800 Btu per lb inert heat dissipation a tube weight of 1.3 lb per lb/min of inert gas is obtained for stainless steel tubes of 0.20 in. OD with 0.008 in. walls, based on heat dissipation proportional to the distance along the tube. And with the inert gas flowing outside the tubes, the heat exchanger shell is a substantial pressure vessel, so that the heat exchanger weight will be considerably more than that of the basic heat transfer matrix.

b. Catalyst Inside the Tubes

A more attractive design from the structural and weight standpoints can be realized by adopting a flow configuration with the ram air outside the tubes, and the inert inside. Since a large inert-side pressure drop can be tolerated at full reactor flow (because for the B-l the output will bypass the gas cooling equipment and go directly to the tanks, and for the TFA the maximum flow occurs at an altitude such that a large reactor pressure drop will still leave adequate pressure to drive the gas cooling equipment), high internal mass flow velocities can be utilized so that lightweight designs are obtained. The high internal velocities place the inside Reynolds number in a range where ring-dimpling of the tube wall provides an effective means of increasing the inside heat transfer coefficient. Additional increases will be obtained due to the turbulence created by the flow of the inert across the catalyst pellets. Also, since the ram-side pressures are less than the inert pressures, placing the inert inside the tubes reduces the weight of the heat exchanger shell.

Because of the large available pressure drop, multipassing of the inert side is feasible so that the overall thermal conductance can be lowered, hence lowering the core weight. A single pass on the ram side must be maintained because of the low pressure drop allowable.

c. Recommendation

In summary, the recommended catalytic reactor flow configuration uses a tubular heat exchanger with the catalyst inside the tubes. For a heat load of 800 Btu per lb inert gas, a four-pass cross-counterflow design will require about 0.6 lb of tubing per lb/min of inert flow. This is based on stainless steel tubes of 0.20 in. OD with 0.008 in. walls.

5. Material Selection

The factors of primary importance in the selection of high temperature heat exchanger materials are mechanical properties, hot corrosion resistance, fabricability, compatibility with brazing filler metals, metallurgical stability, and cost.

The heat exchanger material must have adequate mechanical properties during its design lifetime to withstand the stresses due to thermal transients and fluctuating and steady-state pressure differentials. It is insufficient merely to measure the properties of new, unexposed material, because mechanical properties are almost always degraded by environmental attack and by metallurgical changes such as aging reactions and carbide precipitation. Metallurgical stability and corrosion resistance cannot be considered apart and are important in evaluating mechanical properties.

Erosion resistance is also an important mechanical property. Erosion is caused by solid or liquid particles (catalyst, carbon, or fuel droplets in the system battering against the surface of a material. Although dynamic yield strength and endurance limit can give indications, there is no accurate way to calculate erosion resistance.

Hot-corrosion is the attack on metal alloy components caused directly or indirectly by contact with products of combustion. Included in this term are all synergistic effects that contribute to hot-corrosion such as sulfidation, oxidation, erosion, stress-corrosion, and both static and cyclic stresses.

Based on experience gained from advanced regenerative gas turbines, and other high temperature heat exchanger applications, Type 347 stainless steel has proved to be an excellent material, and is the recommended catalytic reactor material. Carbide precipitation in grain boundaries and consequent sensitization to chemical corrosion at low temperatures are minimized by the addition of columbium, which forms stable carbides. Brazeability of Type 347 is excellent and formability is good. Type 347 has good creep strength and hot-corrosion resistance to approximately 1300°F for long-time service. Thus, designing the catalytic reactor for a maximum material temperature of 1200-1300°F is required.

6. Ram Air Flow Control

If the catalytic reactor is designed in such a manner that at maximum inert flow the bleed air/fuel reaction occurs over almost the entire length of the reactor, then at part loads the reaction will occur in only part of the reactor. This is shown in Figure 8. Depending on the relationship between the flow rate and the reaction length, it is possible that the heat to be dissipated at a specific point within the reactor at part load could equal or exceed that at full load. Thus, if the overall ratio of the ram air flow to the inert flow is fixed, then it is necessary to provide some method of controlling the ram air flow along the reactor length so that flow adequate for the required heat dissipation can be maintained at part loads. Test data will be required to establish the relationship between the heat dissipation and the required local ram air flow; however, it appears that the most desirable concept is regulation of the ram air flow distribution by means of a simple door actuated on the ram inlet side. The concept shown in Figure 9 allows routing the ram flow through only a portion of the heat exchanger at inert flows less than the design condition.

7. Maintenance Considerations

The catalyst packed within the reactor tubes will require periodic replacement. This can be provided by designing the reactor with removable headers. Either encapsulated catalyst or wire screens over the tube pass ends would prevent catalyst loss to the inert gas flow and would prevent excessive fluidization of the bed.

Careful headering and manifolding design will be necessary to ensure good flow distribution through the catalyst bed and to eliminate any possibility of local hot spots.

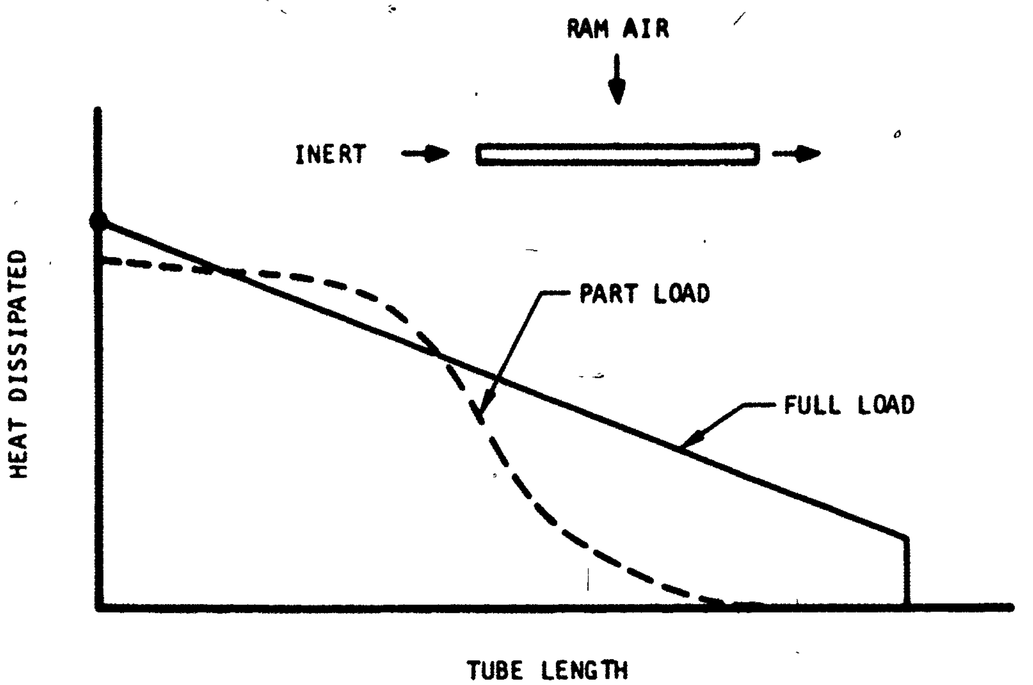


Figure 8. Possible Heat Dissipation Variation with Flow

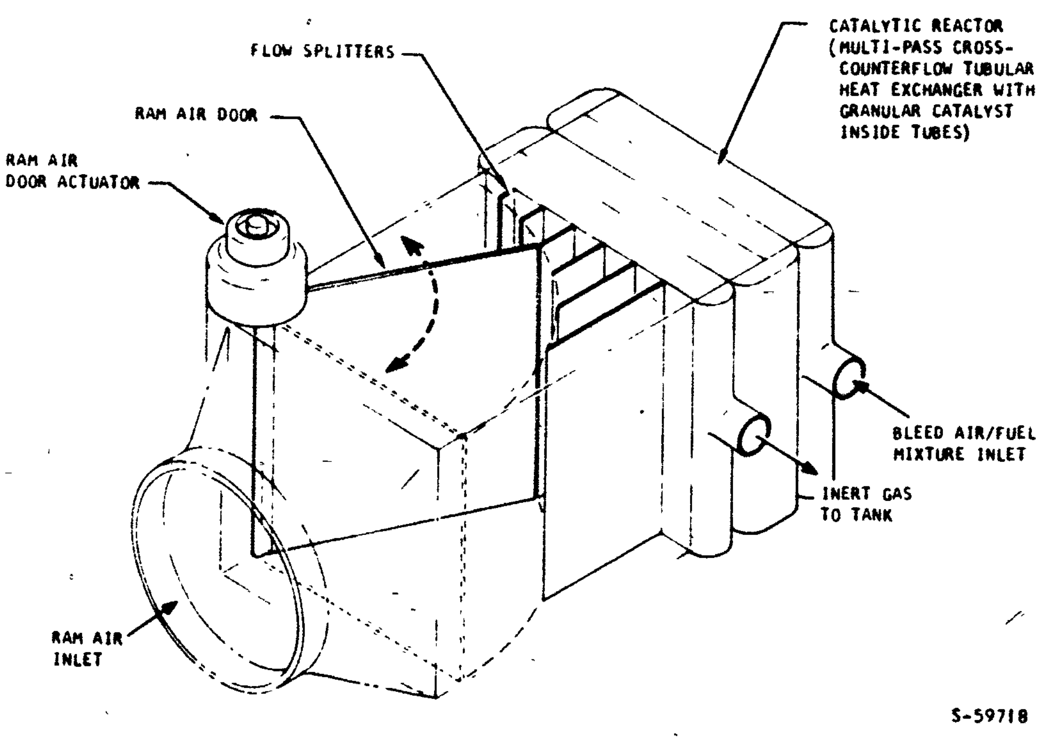


Figure 9. Catalytic Reactor Configuration

8. Design Summary

The catalytic tubular heat exchanger design appears less stringent than that required for advanced gas turbine recuperators, and is within the current state-of-the-art. The design study has indicated the following:

- Lightweight design can be achieved using a compact tubular matrix
- Minimum weight results with the inert gas, and hence catalyst, placed inside the dimpled tubes
- A compact unit can be designed with a single-pass ram air side and a multi-pass inert gas side
- Conventional furnace-brazed 347 stainless steel construction is recommended
- Removable headers on the inert side are required to facilitate periodic catalyst replacement
- Part load performance requires a ram air flow control door on the ram air inlet side of the reactor

Combustion

For the same output product, the fuel required by the catalytic reactor and a combustor will be approximately equal; however, combustion is a less efficient process than reaction and the usual end products of combustion are a combination of CO and CO_2, as opposed to the essentially complete reaction (all CO_2) obtained with a reactor.

Three types of combustors are possible:

- A single-stage combustor, in which the incoming air is used to cool the combustion chamber
- Staged combustors in which the total combustion energy is split into each of several series combustors having interstage cooling
- Bootstrap combustor allowing ram air to be used as the inerting air source

1. Single-Stage Combustor

A single-stage combustor, such as that shown in Figure 10, has been used in previous aircraft fuel tank inerting systems and is covered by US Patent 2,775,238 assigned to D. J. Clark and M. S. Decker. In this concept, the incoming relatively low-temperature air is used to cool the combustor can by causing the air to flow partially around the can prior to injecting it with fuel and burning it. A second can, downstream of the first, completes the combustion process by mixing additional air with the hot, fiery,

incompletely combusted products from the first can. A spark plug is used as the ignition source for the combustor.

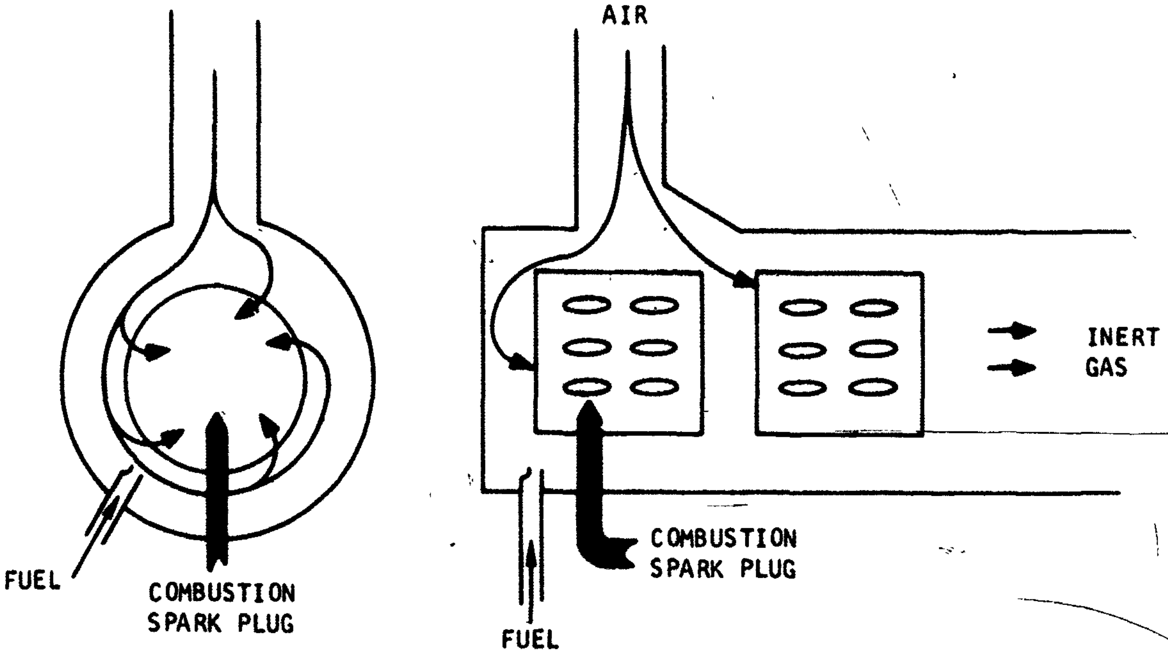


Figure 10. Simplified Schematic of a Single-Stage Combustor

In a single combustor, the equilibrium temperature gain of the reaction products is about 3200°F if 4.2 lb fuel per 100 lb air are used. Proper design will limit the maximum combustor can temperature to levels considerably below this, but the maximum material temperatures will exceed those obtainable with catalytic reaction. Consequently, it can be expected that a combustor would produce more nitrogen oxides and other deleterious compounds than would a reactor. Also, combustors are generally limited in the flow variation that they can handle while still maintaining an efficient reaction.

In most other features, combustor performance will be nearly equal to that for a catalytic reactor. In both concepts, the bulk of the weight will be the heat transfer surface required to cool the inerted gas to reasonable temperatures. Also both concepts require limited periodic maintenance spark plug replacement, cleaning, combustor can replacement in the case of the combustor; and catalyst replacement in the catalytic reactor.

2. Staged Combustors

It is possible to reduce the maximum material temperatures considerably by using staged combustors in which the combustor discharge flow is cooled prior to entering the next combustor. Such units have been used

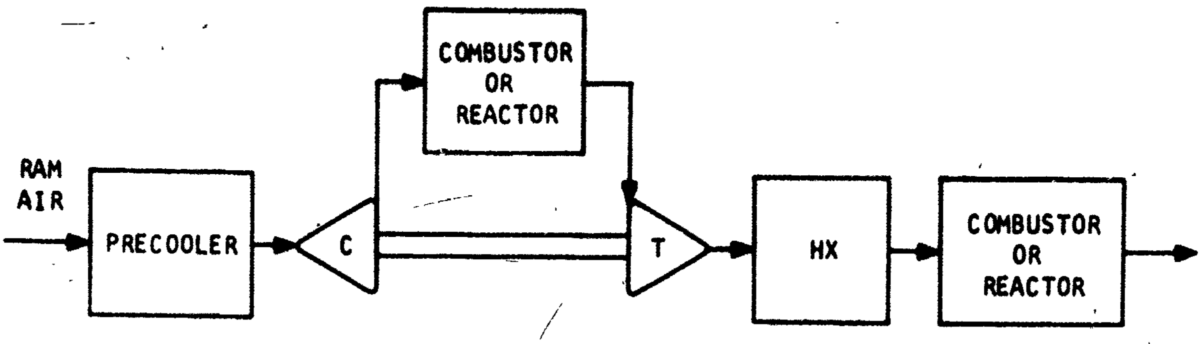


Figure 11. Bootstrap Combustor/Reactor Schematic

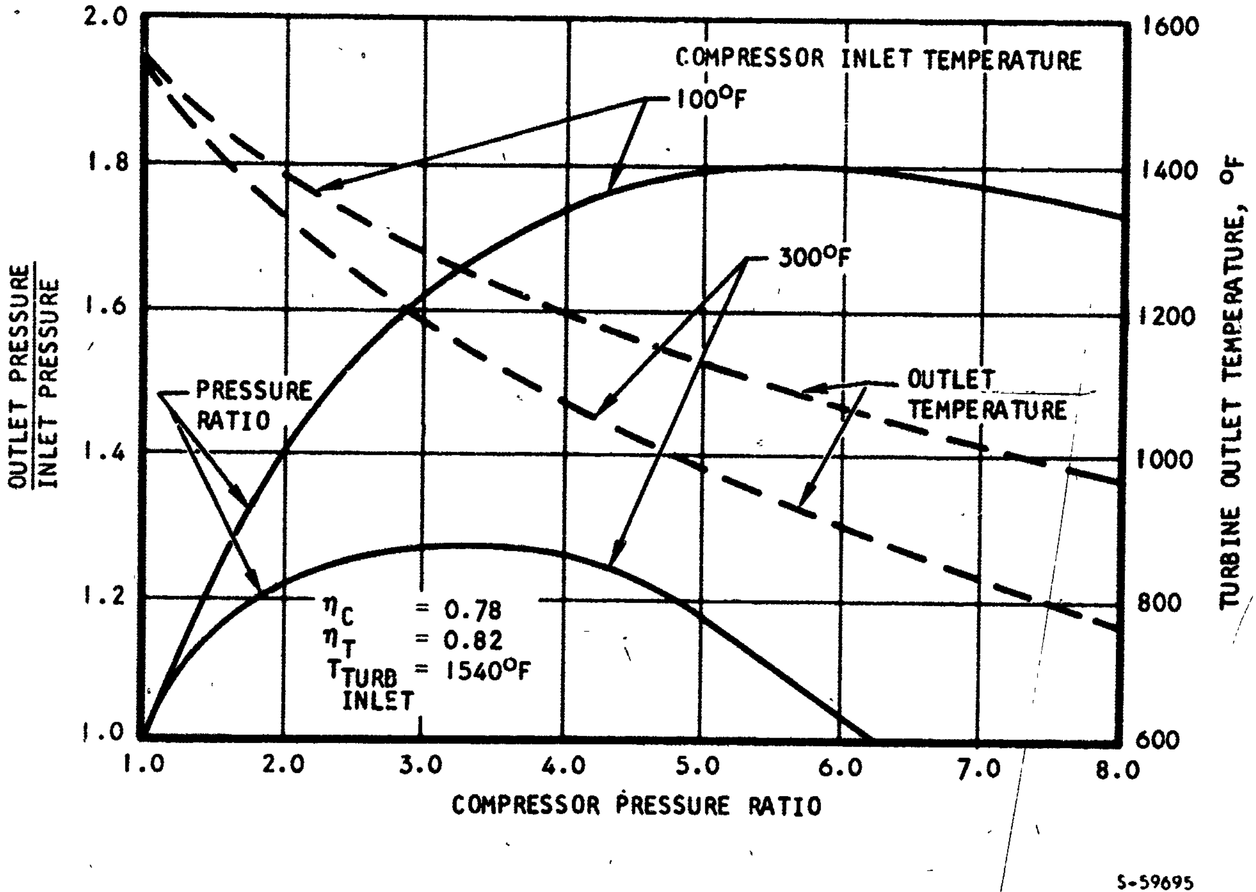


Figure 12. Bootstrap Combustor/Reactor Performance

successfully in research laboratories. However, the overall weight of such a system will be higher than that for a single-stage combustor and the control will be more complex since fuel would be injected in several different places. Thus, staged combustors do not appear competitive with a catalyst bed for this application.

Bootstrap Combustor/Reactor Cycle

It is possible to design an inerting source that could operate on ram air during all flight modes except very low speed flight at high altitudes. Such a cycle is shown schematically in Figure 11. In this concept, ram air is compressed and heated in either a reactor or combustor prior to expansion across a turbine. Materials limitations establish the upper limit on the gas temperature at the turbine inlet; thus, if additional fuel is required to accomplish the necessary oxygen removal (as is the case), then the turbine discharge must be passed through an additional reactor or combustor stage.

Figure 12 shows the pressure increase across the bootstrap machine as a function of the compressor pressure ratio. The data show that there is a strong incentive to have a low compressor inlet temperature if a high pressure ratio is to be obtained. Thus, it will be necessary to place a precooler in front of the compressor to cool the ram air during high speed flight. Also, to obtain the relatively high compressor pressure ratio at which optimum performance is obtained, it may be necessary to use a multi-stage compressor.

This cycle will weigh more than will either the reactor or single-stage combustor cycles, and it requires more components and a more complex control system (because there are two separate points at which fuel must be injected into the process stream). Thus, unless there is an extremely strong incentive to limit the use of bleed air, the bootstrap combustor/reactor cycle does not appear to be competitive for this application.

Adsorption Processes

Regenerable adsorption beds can be used as a means of obtaining a nitrogen-rich output gas flow. The concept is shown schematically in Figure 13 and described in U.S. Patent 2,944,627 (by C. W. Skarstrom, assigned to Esso). This system depends upon preferential adsorption of oxygen by synthetic zeolite (molecular sieve) adsorbents. High-pressure air is passed through an adsorbent bed that removes oxygen to provide a concentrated nitrogen effluent. As shown in Figure 14, for a product gas with a residual oxygen content of about 5 percent by volume, about 20 percent of the input flow will appear as nitrogen-rich output; the remaining flow will be discharged overboard. It is possible to input the secondary effluent from one set of beds to a second set so that the amount of wasted bleed air is minimized; however, such a concept would require compressors and pumps to compensate for the pressure differences between the various beds.

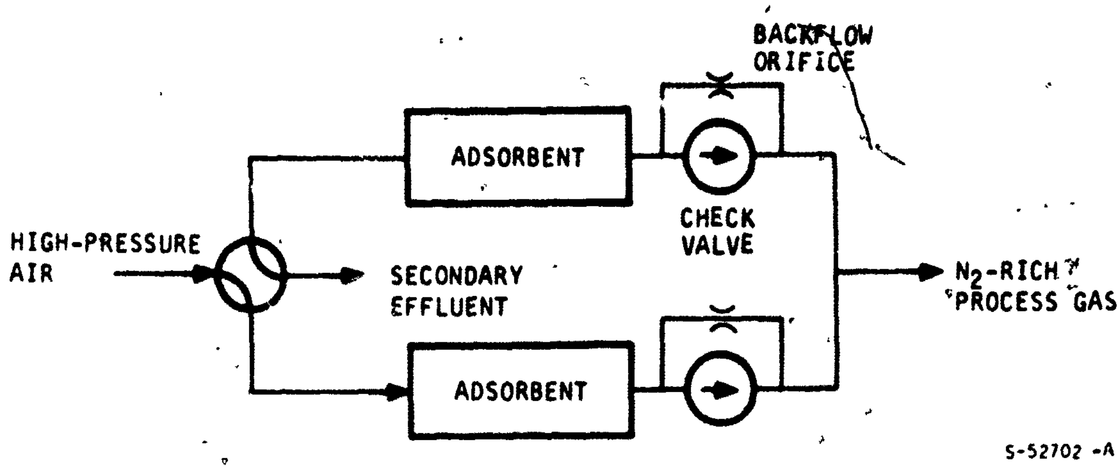


Figure 13. Nitrogen Separation from Air by Adsorption

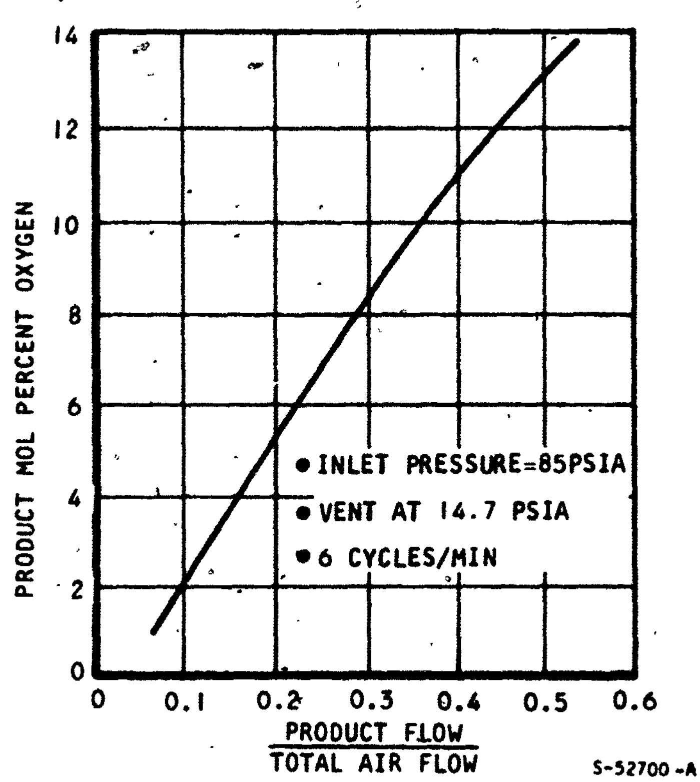


Figure 14. Nitrogen Enrichment by Adsorption

The sorbent material is capable of carrying about 0.01 lb/min of process flow per lb material at 70°F and 85 psia inlet. This ratio can be improved by lowering the inlet temperature to the bed, or by raising the pressure. However, this high fixed weight, combined with the inefficient use of bleed air, eliminates adsorption processes from further consideration.

Absorption Processes

Regenerable absorbents for removing oxygen from air are being investigated at AiResearch under Air Force contract F33657-69-C-1187. These absorbents can also be used to generate a nitrogen-rich inert gas. The process consists of flowing bleed air through a bed which absorbs oxygen to obtain a nitrogen-rich effluent. After a period of time, the air flow is reduced to a very low value and the bed is heated to about 180°F. Pure oxygen desorbs from the bed and is swept out with the low air flow. The bed is cooled to 60°F and the process is repeated. With two beds, a constant supply of inert gas can be obtained. Figure 15 shows a schematic of such a system employing elements of an environmental control system to provide bed heating and cooling.

For a 10 min cycle time on the beds, and an output having an average oxygen concentration less than 7.8 percent by volume, the following performance data are obtained:

- Process gas pressure = 35 psia
- Process gas flow = 0.17 lb/hr per lb absorbent
- Inerting flow = 0.15 lb/hr per lb absorbent

Increasing the inlet pressure to about 150 psia increases the process flow to 0.73 lb/hr per lb absorbent and the inerting flow to 0.62 lb/hr per lb absorbent. These data assume that the beds use salcomine (bisalicylaldehyde ethylenediamine-cobalt), which is the most effective oxygen absorbent tested to date. However, a new, untested compound having superior characteristics may allow considerable increases in the gas flows, possibly by as much as a factor of 7.

The bed cooling and heating requirements are each about 280 Btu/lb inert. Thus, if bleed air at 475°F, 35 psia is used, about 4 lb bleed air/lb inert would be required to provide the heating requirement. The cooling requirement would require an additional 40 lb bleed/lb inert, based on 32°F outlet temperature from an air cycle machine. Also, it would be necessary to use ram air as a heat sink for the refrigeration cycle. Additionally, the high oxygen content in the gas generated by the absorption process would necessitate using a different gas source to provide the low oxygen content required during fuel scrubbing on the initial aircraft climb.

Clearly, the total heat load penalties combined with the requirement for a supplemental gas source to accomplish scrubbing, eliminate this concept from further consideration.

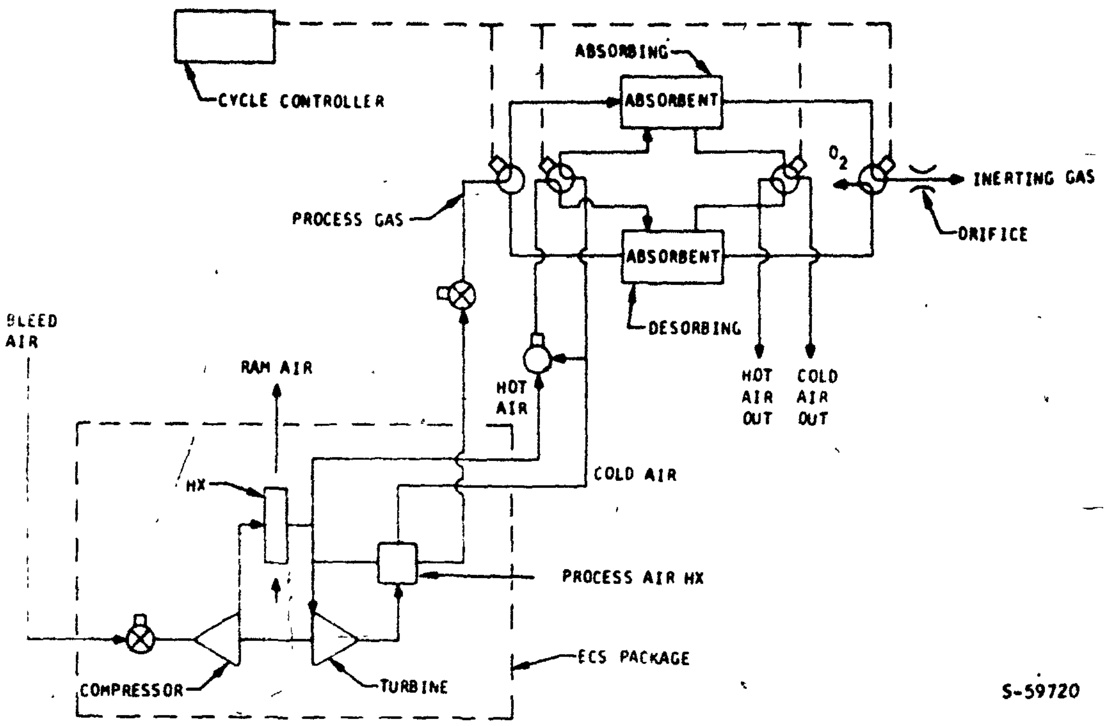


Figure 15. Nitrogen Separation from Air by Absorption

Electrochemical Processes

Electrochemical cells to remove oxygen from air have been investigated by the Air Force as a means of supplying breathing oxygen to flight crews. This approach could be used for the inerting system to supply a nitrogen-rich flow to the fuel tanks.

Information from TRW, Inc., Mechanical Products Division (that has had several electrochemical cell contracts, including AF33615-3392, AF33615-1856, and NAS2-4444) indicates that about 1.2 to 1.5 kw of dc electrical power is required to separate a flow of 1 lb/hr of oxygen from air. Thus, for an inerting system having an output with 5 percent oxygen by volume, the power requirement is 15 to 20 kw per lb/min of inert. Also, TRW indicated that the fixed weight of an electrochemical system is about 15 lb/lb/hr of oxygen for small systems having up to 5 lb per hr of oxygen output; thus, for an inerting system, the fixed weight would be about 165 lb per lb/min of inert flow. Clearly both the electrical power required by the electrochemical cell and its weight make this concept noncompetitive as an inerting gas source.

Inert Gas Source Selection

Only the catalytic reactor and the combustor concepts provide designs of reasonable weight and power for a fuel tank inerting system. The adsorption, absorption, and electrochemical processes are noncompetitive for this application. The catalytic reactor has been selected as the inert gas source for the following reasons:

- Its weight will be less than that of an equivalent combustor concept

- It operates at lower temperatures and hence can utilize conventional materials

- Its efficiency is essentially 100 percent; thus there will be no fuel or carbon carryover into the remainder of the system

- Its only maintenance requirement is periodic catalyst replacement, whereas the combustor requires cleaning, spark plug changes, power supply maintenance, etc

GAS COOLING AND MOISTURE REMOVAL CONCEPTS

Generating inert gas with a catalytic reactor results in the addition of considerable heat and moisture to the process flow. Thus, it becomes necessary to cool the gas prior to allowing it to enter the fuel tanks. Additionally, the moisture content must be lowered considerably from the approximately 611 grains H_2O per lb dry inert that exist at the catalytic reactor outlet. Much or all of this moisture removal can also be accomplished by cooling the gas, causing moisture to condense.

The material below examines the design point performance capabilities of three types of cooling methods for an assumed design point that has been selected based on similarity of the IGG to aircraft environmental control systems. The three cooling classifications are:

- Direct cooling by heat rejection to heat sinks

- Vapor cycle refrigeration

- Air cycle refrigeration

The data presented indicate that direct heat rejection alone can not provide low outlet moisture contents. Thus, it is necessary to use either a refrigeration system or a sorbent bed to remove the excess moisture. The data also show that both vapor cycle and air cycle refrigeration systems can provide extremely low outlet moisture contents. Selection of the preferred gas cooling technique involves combining the cooling concepts with the supplemental moisture removal concepts to obtain systems meeting both the temperature and moisture requirements. These systems are synthesized after examination of the sorbent bed performance capabilities.

Assumed Cycle Design Point

The selected cooling and moisture removal concept must be capable of providing the required heat removal over the entire aircraft operating regime; however, the inerting cycle will be designed to meet the performance goals at a single point, having excess heat removal capacity under all other operating conditions. In general, this point will occur at the following operating conditions:

- Minimum engine bleed air pressure--this minimizes the moisture removal that can be accomplished by cooling the gas to a given temperature - saturation occurs at higher moisture contents as the pressure is decreased.

- Maximum delivery pressure--for a given bleed pressure, this minimizes the amount of cooling obtainable by passing the inert through an expansion turbine; that is the expansion ratio is minimized

- Maximum flow requirement--this maximizes the total heat rejection required as well as sizing the components (note that at lower flows, the heat transfer equipment will operate at higher effectiveness, if the cooling flow is maintained, thus giving higher heat removal per unit process flow

- Maximum heat sink temperatures

The point satisfying these conditions is when the aircraft is in idle descent (minimum bleed pressure), at sea level (maximum delivery pressure), with empty tanks in a steep dive (maximum flow requirement), on a hot day (maximum heat sink temperatures for the other operating conditions. Although higher heat sink temperatures occur (most notably when the aircraft is in supersonic flight), the bleed and delivery pressures are such as to make efficient moisture removal possible.

For aircraft environmental control systems, which also must provide cooling and moisture removal over the aircraft operating regime, the heat exchangers and rotating equipment performance are determined with the aircraft in idle descent. However, the ram air circuit is sized on the ground where it is necessary to provide a ground cooling fan in order to pass the required cooling flow through the heat exchangers. This combination of conditions will also probably size the IGG components since they must be capable of providing the maximum normal descent flow during the final phases of descent, and also providing high flows while the aircraft is on the ground for fuel scrubbing and initial tank pressurization.

Thus, the material presented in the remainder of this section will analyze the performance capabilities of various concepts under the following conditions:

- Throttle setting--idle (bleed air pressure assumed to be 35 psia)

- Airspeed--Mach 0.70 (this is somewhat above the maximum speed occurring during the final phases of descent--although the aircraft can obtain considerably higher speed at sea level, these conditions result in a higher throttle setting and consequently a higher bleed air pressure)

- Altitude--sea level (requires IGG discharge pressure of about 15.7 psia to accommodate the distribution ducting pressure drop and the tank pressure of about 0.5 psig)

- Day--MIL-STD-210 hot day

<u>Direct Cooling by Heat Rejection to Heat Sinks</u>

Direct heat rejection involves process gas cooling by heat transfer to a heat sink. There are numerous heat sinks available on the aircraft, including:

- Ram air

- Engine or APU bleed air

- Fuel

- Expendable evaporant

- Structure

- Hydraulic fluid

- Oil

- ECS chilled air

The first four heat sinks are open cycle concepts in which the heat sink fluid is either vented to ambience after use, or passed into the engine for oxidation (in the case of fuel). The latter four concepts involve a two-step process in which the heat is rejected to the first heat sink (that listed) prior to later rejection to the ambience, via air cooling.

1. <u>Temperature</u>

The primary variable involved in heat sink selection is the desired heat rejection temperature. To obtain an outlet moisture content less than 80 grains per lb dry inert, the graph of Figure 16 indicates that the heat sink temperature must be a maximum of 75°F if the process gas pressure is 35 psia. The data of Figure 16 also show that passing the process gas through an expansion turbine and water separator after cooling allows the heat sink temperature to increase to 93°F while still maintaining the outlet at 80 grains moisture. Other refrigeration cycles, presented later, will allow somewhat higher heat sink temperatures while still maintaining the

desired 80 grains moisture in the output. However, the data indicate that there is strong incentive to obtain low heat sink temperatures. Consequently, it is possible to eliminate using engine bleed or APU bleed as a heat sink (their temperature always is in excess of about 400°F). Also, most of the aircraft structure will exceed 150°F at the assumed IGG design point, making it an undesirable heat sink.

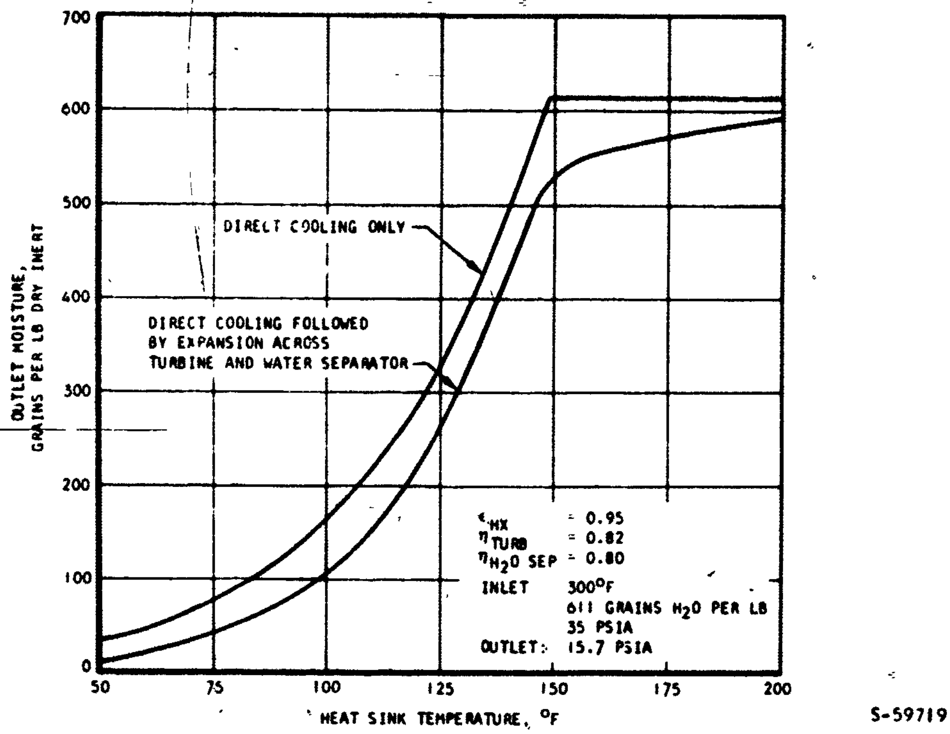


Figure 16. Outlet Moisture vs Heat Sink Temperature

2. Heat Sink Flow Availability

At the assumed design point, about 140 Btu per lb of inert must be rejected to obtain 80 grains per lb outlet moisture. This requires relatively high cooling fluid flows: about 3 lb air per lb inert, or about 1.5 lb fuel, oil, or hydraulic fluid per lb inert. The flow requirements for either oil or hydraulic fluid are probably in excess of the available flows and, additionally, the hydraulic fluid flows would only be available on an intermittent basis unless special provisions were made for the IGG. Thus oil and hydraulic fluid have been eliminated from further consideration. Also, it would be undesirable to use fuel, oil, or hydraulic fluid as the catalytic reactor heat sink since a failure causing leakage into the reactor could result in a fire hazard, as well as causing coking and carbon deposition on all of the components downstream of the reactor.

Of the possible expendable heat sinks, such as water, Freon, etc, the total heat load during a mission is such as to eliminate them from consideration. Additionally, it should be noted that their use would necessitate IGG servicing after each flight.

Consequently, it appears that air is the only heat sink acceptable for the catalytic reactor; it is also an excellent heat sink during subsonic flight for all other heat transfer surfaces. Additionally, fuel might be used for other cooling loads (where there is no fire hazard). During supersonic flight when the ram air temperature greatly exceeds the fuel temperature, fuel becomes a particularly attractive heat sink for all heat transfer surfaces except the catalytic reactor.

3. Use of ECS Chilled Air

Using ECS chilled air for the IGG would necessitate an increase in the ECS size. Thus, it becomes necessary to trade the ECS and ECS-to-IGG heat exchanger weights against the weights of separate ECS and IGG systems. Using ECS chilled air greatly simplifies the design of the IGG, although it does make its performance dependent upon that of the ECS. Figure 17 shows how the ECS air would be used for the IGG both to cool the process gas during its reaction with the fuel and to provide moisture and temperature control. The figure shows 2 ECS packs (for B-1); however, the TFA has only a single ECS pack.

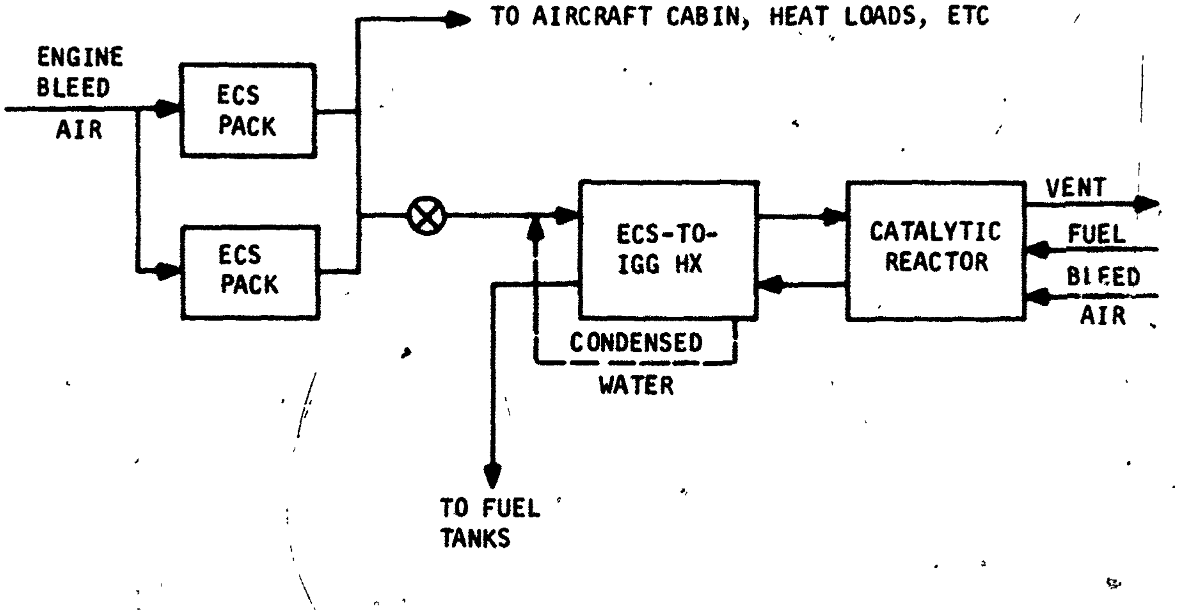


Figure 17. Possible ECS-IGG Integration

This concept eliminates the ram air duct that is required for an IGG using ram air cooling; thus, the inerting system can be located without regard to ram air availability. However, it should be noted that such a concept does not use any of the refrigeration potential available in the IGG process flow (pressure head available to expand and cool the gas). Also, using ECS air for cooling means that there is increased use of aircraft engine bleed air (ECS and IGG both use bleed air). Generally, the equivalent fuel consumption increase necessary to offset bleed air usage is from 3 to 6 times that necessary to offset ram air usage.

The total fixed weight of the ECS chilled air IGG will be somewhat less than that of the ram air cooled IGG; however, the higher operating penalties for the ECS chilled air concept (about 50 percent more fuel consumption), combined with the interdependence of the ECS and IGG performance that is obtained by this type of integration, appear to make this concept unattractive.

4. Ram Air Properties

Ambient ram air will be compressed as it passes into a ram air duct, giving a recovered pressure substantially in excess of the ambient pressure. This pressure rise in turn causes a temperature rise in the air. Figure 18 plots the ram air temperature vs altitude for various aircraft airspeeds.

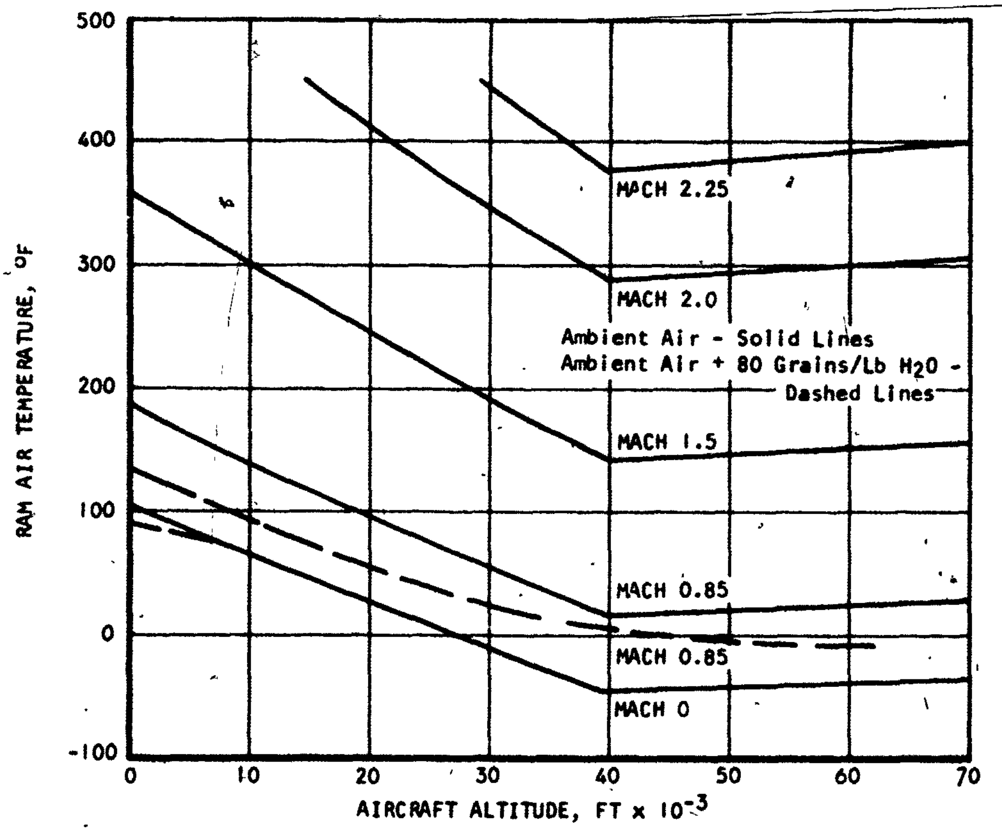


Figure 18. Ram Air Temperature vs Aircraft Altitude on MIL-STD-210A Hot Day

By spraying the moisture condensed in the IGG into the ram air, it is possible to lower the ram air temperature. The dotted lines of Figure 18 show the ram air temperature after vaporization of moisture from the process stream. Since the process gas will have a minimum of 418 grains moisture per lb, it is possible to add at least 80 grains moisture per lb to the ram air, based on a ram airflow 5 times the inert flow. The data are based on an ambient humidity per MIL-STD-210, Figure IV. Lower ambient humidities, as will normally be the case, will result in lower ram air temperatures when water is injected into the ram airflow.

At the assumed IGG design point, the ram air will have a temperature of 160°F. Water injection lowers the ram air temperature to 102.5°F. Thus, the process stream could be cooled to about 112°F, which would give 178 grains per lb moisture at 35 psia. Clearly, it will be necessary to provide additional cooling in order to obtain satisfactory moisture control. This cooling can be obtained by the refrigeration cycles discussed later.

5. Recommended IGG Heat Sinks

Based on the above information, the IGG gas cooling concepts presented later in this section use either ram air or fuel as the cycle heat sinks. The catalytic reactor will use only ram air during both subsonic and supersonic flight since using fuel might cause a safety problem. The gas cooling equipment will use both ram air and fuel for heat sinks. Ram air is the preferred heat sink during subsonic flight since its temperature, when saturated with process flow water condensed by the cooling cycle, will be less than the fuel temperature, for aircraft altitudes above about 15,000 ft (see Figure 18). During supersonic flight, fuel is the preferred heat sink for the refrigeration equipment since its temperature will almost always be less than the ram air temperature.

Vapor Cycle Refrigeration

In a vapor cycle refrigeration system an intermediate working fluid is used to reject the IGG heat load to ambience. Figure 19 shows a schematic of the basic vapor cycle system as applicable to the IGG. The working fluid, usually Freon, is compressed and condensed by using ram air as the heat sink prior to expanding the fluid into the evaporator where it absorbs the heat rejected from the inerted output of the catalytic reactor.

Ideally, the system would use fuel as the condenser heat sink. However, at idle setting on the engine throttle, the fuel flow to the engine is insufficient to allow the IGG to operate at full normal flow. Thus, it is necessary to either recirculate the fuel to provide adequate flow or to use ram air as the heat sink. Since ram air cooling will also be required by the catalytic reactor, it appears that the weight-optimum approach is to also use ram air cooling for the Freon condenser during subsonic flight (condenser must be fuel cooled during supersonic flight). The weight of the ram air-to-Freon heat exchanger will be considerably less than the weight of a fuel recirculation pump and lines.

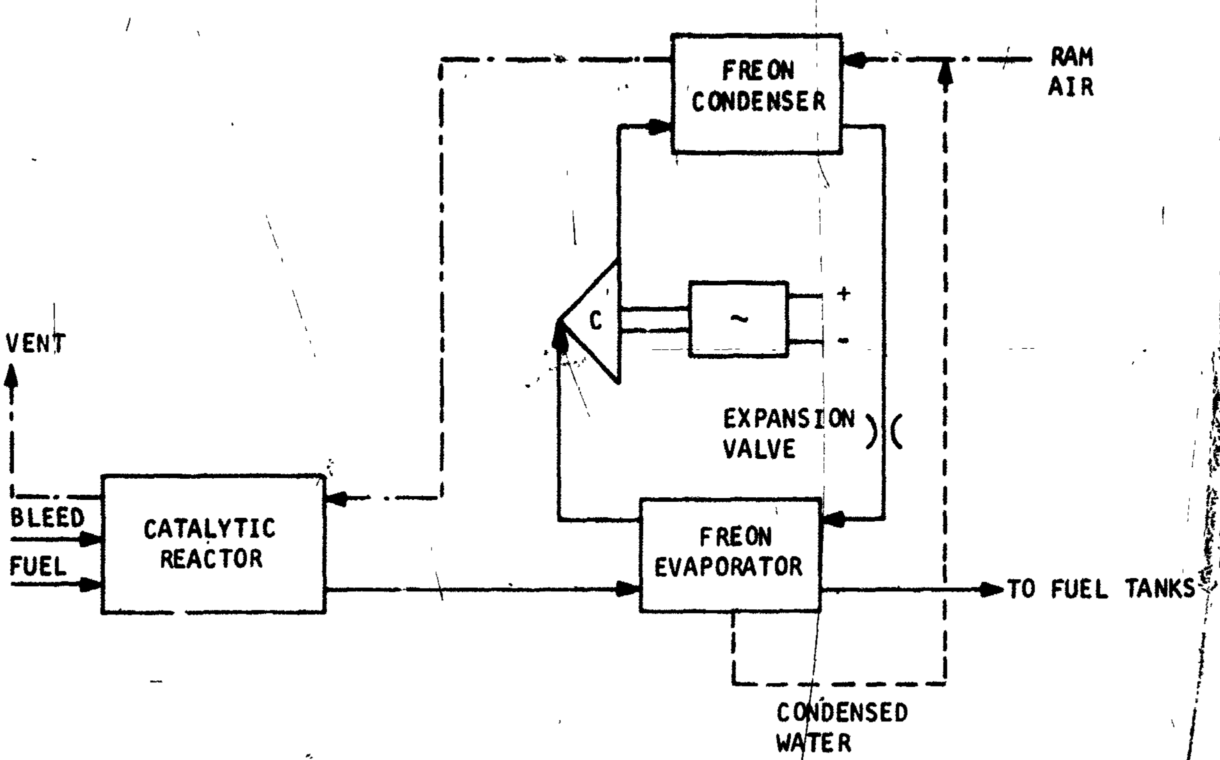


Figure 19. Possible IGG Vapor Cycle Refrigeration System

Figure 20 shows the performance potential for a Freon system per the schematic of Figure 19. The data indicate that a discharge moisture content of 80 grains per lb can be easily obtained. At this condition, the compressor will require about 1.15 kw per lb/min of inert flow, or about 77 kw on the B-1 and 41 kw on the TFA. These power requirements would occur during the final phases of landing at the same time that the other electrical loads are at a peak; therefore, using an electrical drive for the Freon compressor would require that the electrical power system capacity be increased. An alternate approach is to use engine bleed air expanded across a turbine to drive the compressor.

One disadvantage of the Freon cycle shown in Figure 19 is that it does not utilize any of the refrigeration potential in the inert flow. Since the inert flow is at about 35 psia, and the delivery pressure is only 15.7 psia, it is possible to obtain considerable work and cooling by expanding the inert flow across a turbine. The work output can then be used to assist in driving the Freon compressor as is shown in Figure 21. Alternatively, this work could be used to drive a fan that will pull air through the ram heat exchangers when the aircraft is on the ground. In either case, the expansion both reduces the cycle power requirement and increases the cooling performance. However, placing vapor cycle and air cycle components on the same rotating shaft generally leads to shaft sealing problems.

An additional method of improving the cycle performance consists of using the inert flow to absorb a part of the condenser heat load as shown in Figure 22.

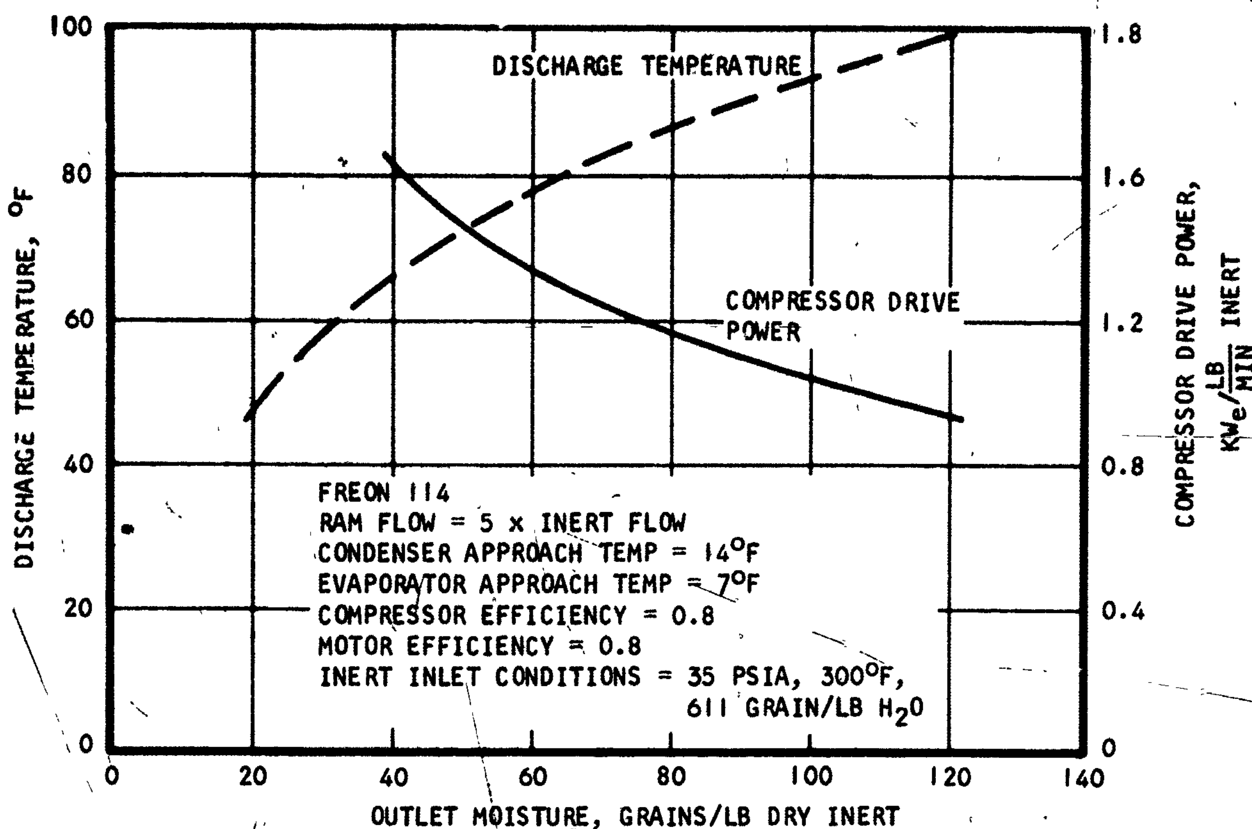


Figure 20. Basic Vapor Cycle Performance

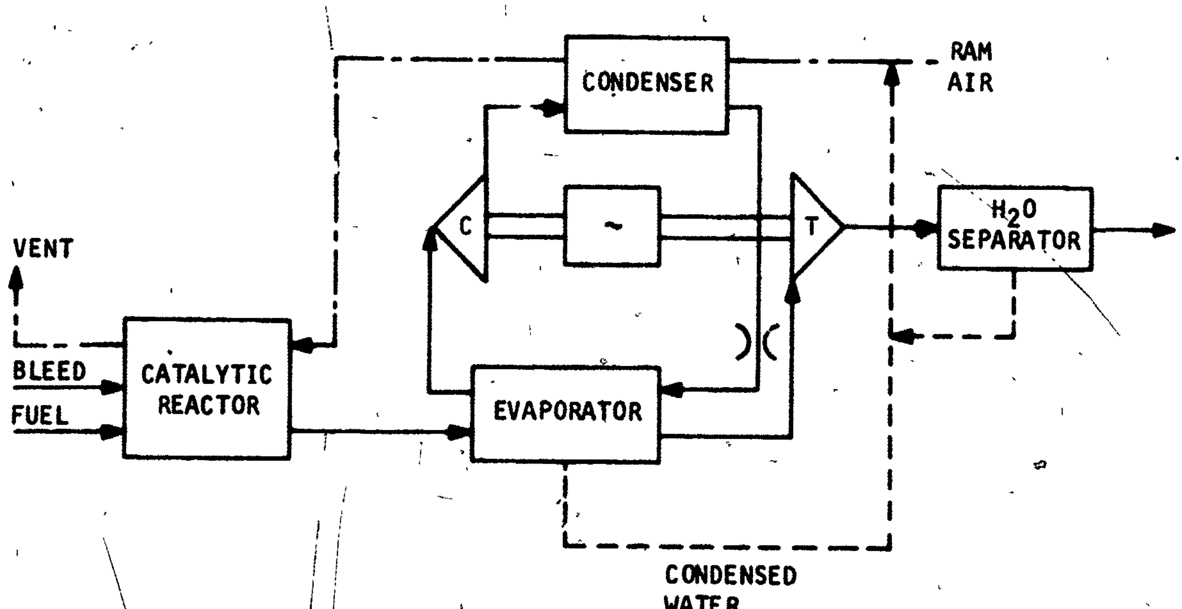


Figure 21. Compound Freon/Air Cycle

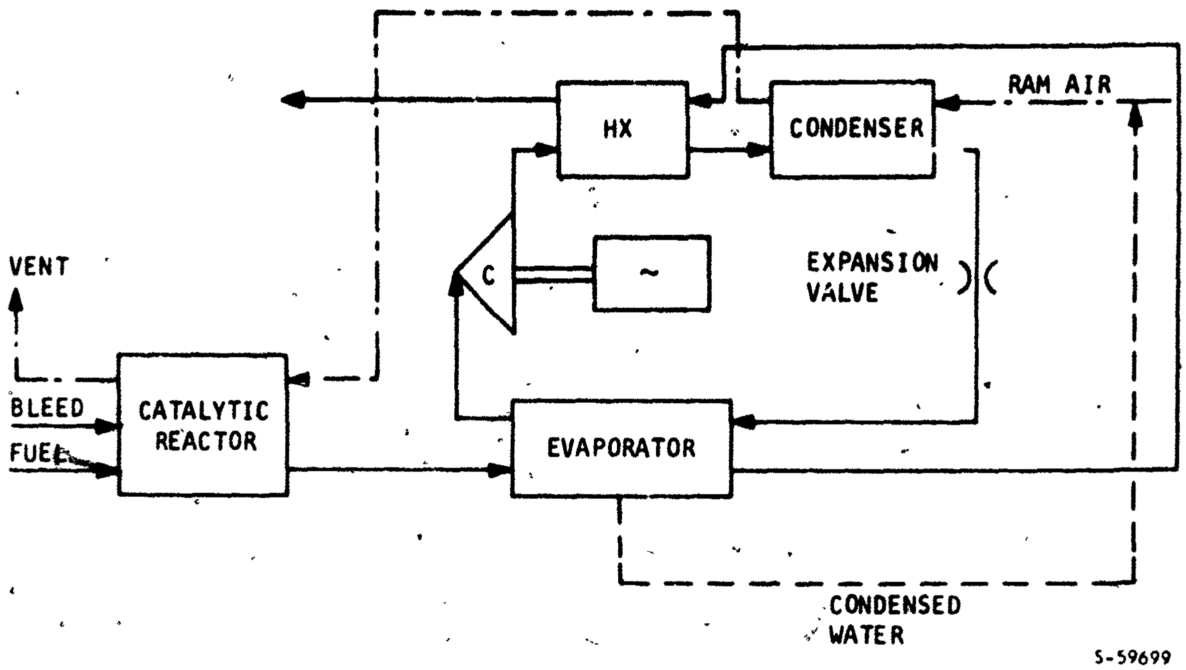


Figure 22. Freon Cycle with Reduced Ram Air Flow

Adding 100°F to the inert flow will still maintain its temperature within the acceptable limits and will account for about 16 percent of the total condenser heat load, allowing an increase in the vapor cycle performance.

Although the above data indicate that vapor cycle systems can easily meet the IGG performance requirements, their high power requirements, or cycle complexity (if inert pressure potential is used to drive the compressor), will probably not make them optimum for supersonic aircraft. Vapor cycle refrigeration systems have only been found weight competitive for aircraft environmental control systems when the total heat loads are such as to require a cooling airflow (if air cycle systems are used) significantly in excess of that required by the cabin for ventilation flow. In such a case, the superior efficiency of the vapor cycle tends to offset the fact that the air cycle system, assuming bleed air is used, can obtain much or all of its refrigeration capacity directly from the bleed air at no weight or power penalty.

Air Cycle Refrigeration

Air cycle refrigeration systems utilize the pressure available in the bleed air to obtain gas cooling by expansion. There are two types of air cycle systems:

- Simple cycle in which the gas is expanded from the bleed pressure directly to the discharge pressure required by the fuel tanks (ignoring slight pressure differences due to component pressure drops)

- Bootstrap cycle in which the gas is first compressed to a pressure above the bleed air pressure, then cooled by heat rejection to a heat sink, and then expanded to the discharge pressure required by the fuel tanks

Each of these basic types of air cycle systems has a number of variations that can be selected to improve the performance.

1. Basic Cycle Dry-Air-Rated Performance

Figure 23 shows the dry-air-rated (DAR) performance capabilities of the basic simple and bootstrap air cycle systems. Both systems have approximately the same weight and, as shown, are provided with identical heat transfer capacity (precooler for the simple cycle and heat exchanger for the bootstrap cycle). In the simple cycle concept, the process gas is cooled and then expanded across a turbine; the turbine work is used to drive a fan that increases the flow of ram air across the precooler. In the bootstrap cycle, the gas is compressed, then cooled, and expanded across a turbine. In the performance data shown, the compressor pressure ratio has been selected such that all of the turbine output work is absorbed by the compressor. Later material shows alternate cycles in which a portion of the turbine work is used to drive a fan that will increase the ram airflow across the heat transfer equipment.

The data in Figure 23 indicate that the bootstrap cycle provides about 30 to 50°F additional cooling (or about 7 to 12 Btu/lb throughflow) in comparison to the simple cycle, depending upon the inlet pressure. This additional cooling can be used to provide a lower moisture content in the discharge gas than is obtainable with the simple cycle.

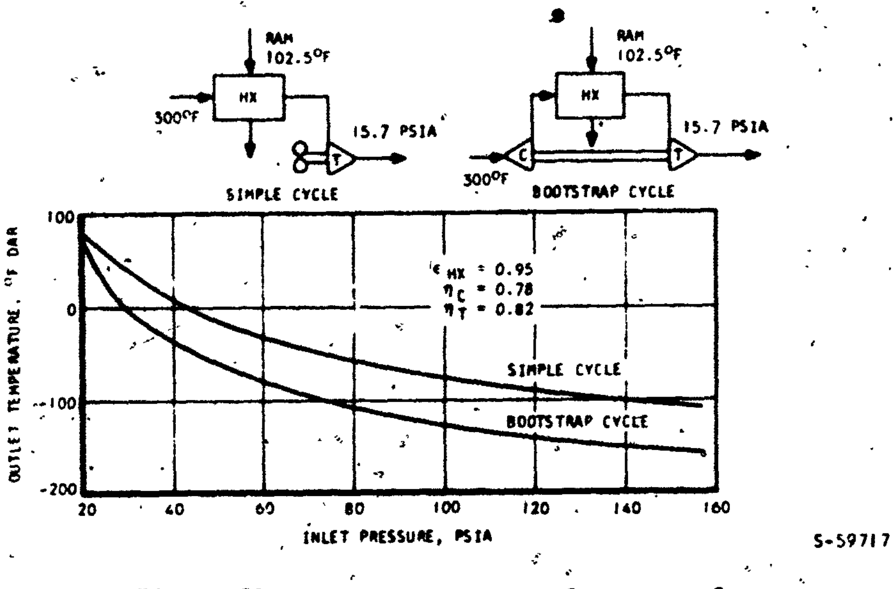


Figure 23. Dry-Air-Rated Performance of Simple and Bootstrap Cycles

2. Basic Cycle Outlet Moisture Content

Figure 24 shows the temperature and moisture content of the discharge flow from both simple and bootstrap air-cycle refrigeration systems. The data are for the assumed IGG design point with the aircraft in idle descent at sea level on a hot day cruising at Mach 0.7. Table 5 shows the assumptions used in deriving the data of Figure 24. The figure shows performance data for a single simple cycle concept and for four different types of bootstrap cycles, three of which use a compressor having a pressure ratio of 1.4, and the fourth having a compressor pressure ratio as required to obtain an internal power balance on the rotating component (such that turbine work output matches compressor drive power without having any extra power available to drive an external load, such as a fan).

a. Simple Cycle

In the simple cycle system, the best performance is obtained at about 32°F with 45 gr of moisture in the discharge; such a condition occurs at an inlet pressure of about 52.5 psia. Higher inlet pressures would cause freezing of the entrained moisture in the turbine discharge stream. The bleed pressure of 35 psia at the assumed IGG design point limits the discharge to about 67°F and 112 gr/lb of moisture, for the assumed cycle inlet temperature of 300°F.

TABLE 5

ASSUMPTIONS FOR FIGURE 24

Heat exchanger effectiveness	0.95	Ambient moisture	182 gr/lb dry air (MIL-STD-210 hot day)
Compressor efficiency	0.78	Ram recovered pressure	16.85 psia
Turbine efficiency	0.82	Ram recovered temperature	160°F
Water separator efficiency	0.80	Ram recovered saturation temperature	102.5°F
Inert inlet temperature	300°F	Ram recovered saturation moisture	277 gr/lb dry air
Inert inlet moisture	611 gr/lb dry inert	Inert discharge pressure	15.7 psia
Aircraft airspeed	Mach 0.70 (idle descent)		
Aircraft altitude	Sea level		
Ambient temperature	103°F (MIL-STD-210 hot day)		

b. Two-Wheel Bootstrap

The bootstrap cycle shown as concept B uses all of the available pressure head to provide refrigeration of the process flow. Thus, the performance obtainable with this concept represents the optimum obtainable with a bootstrap cycle without a precooler. The best performance occurs at 32°F and 45 gr/lb moisture content with an inlet pressure of about 36 psia. At the assumed IGG design point, this cycle provides an outlet having 51 gr/lb moisture at 37.5°F.

At 35 psia inlet pressure, the compressor pressure ratio is about 1.63 for a turbine/compressor power balance. Using a compressor having a pressure ratio of only 1.4 would allow about 32 percent of the turbine output work to be used to drive a fan (as per concepts D and E). In such a case, the output moisture content will be somewhat higher, but the fan power can be used to increase the flow of ram air across the heat exchangers. Concept B will also require a fan, which must be driven by some external power source, such as an electric motor, an expansion turbine using bleed air, etc. Thus, although concept B offers superior performance, it requires an additional independent component (a separately driven fan).

Concept C is also a two-wheel concept in which only a portion of the total flow is passed through the turbine. The remainder of the flow bypasses the turbine to provide a power balance. Thus, a large portion of the refrigeration available is wasted. This indicates that the selected cycle should be designed for full flow through the turbine at the design point.

c. Three-Wheel Bootstrap

Many of the recent aircraft environmental control systems have been designed as three-wheel bootstrap machines in which the third wheel is a fan so that the number of components is minimized. Thus, it appears possible that such may also be desirable for fuel tank inerting systems. Consequently, the remainder of the data presented for bootstrap cycles assume a three-wheel machine in which a portion of the turbine output power is used to drive a fan. It should be noted that the performance difference between the two-wheel and three-wheel concepts is relatively slight; equivalent cycles have a difference of about 16 gr/lb moisture in the discharge.

Figure 24 shows performance data for the two different three-wheel bootstrap cycles in which a portion of the turbine output power is used to drive a fan, one with and one without a precooler. Both concepts use a compressor having a pressure ratio of 1.4. Concept D provides discharge conditions of about 45 gr of moisture at 41 psia without freezing. At the assumed IGG design point, this concept would yield about 67 gr/lb moisture at a temperature of 47°F; about 25 percent of the turbine work is used to drive the fan.

The final concept shown in Figure 24 is similar to concept D, except that a precooler has been placed in front of the compressor. The addition of the precooler allows this bootstrap concept to provide as little as 42 gr/lb moisture at 32°F at the assumed IGG design point inlet pressure; about 42.5 percent of the turbine work is used to drive the fan. This concept has about twice as

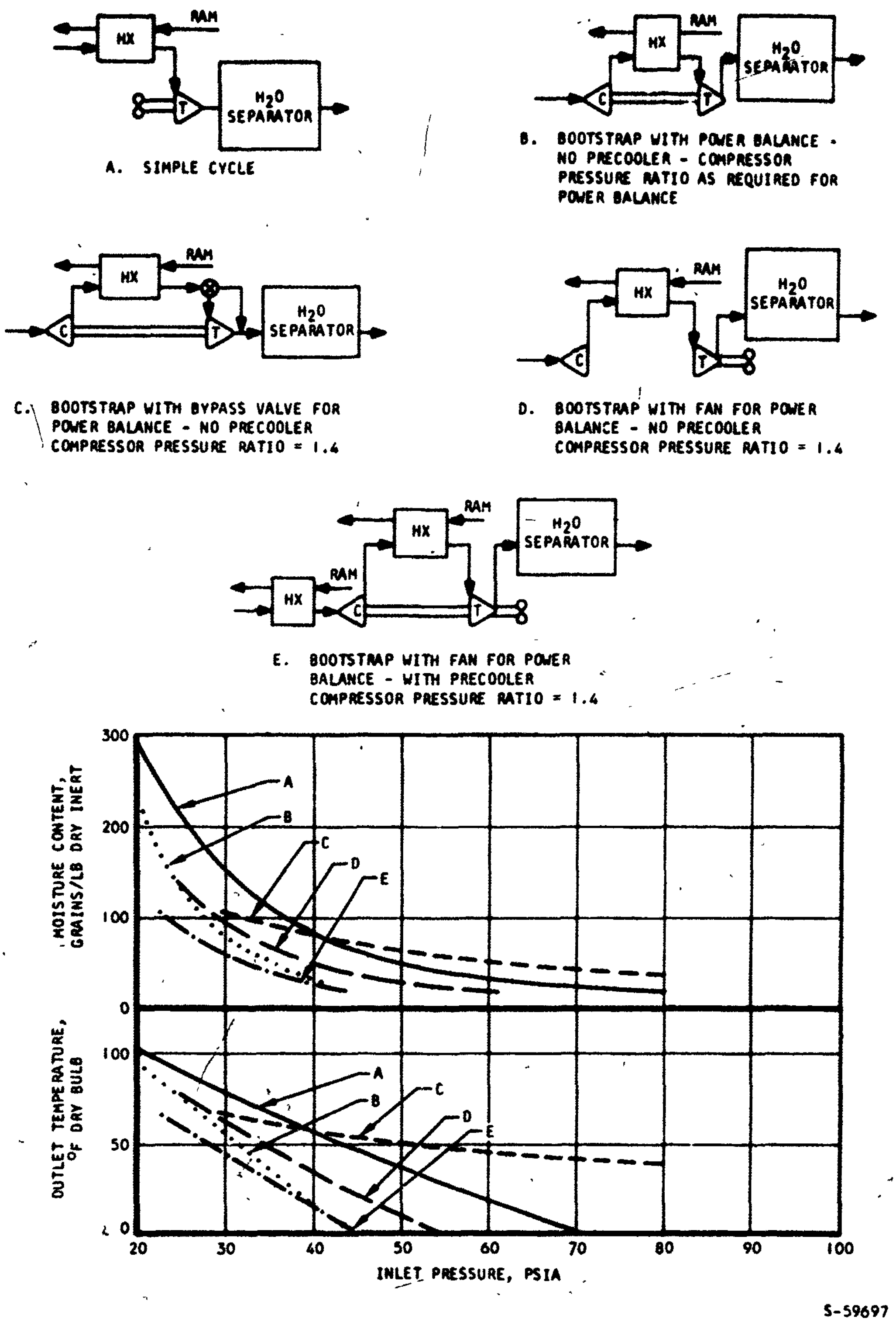


Figure 24. Outlet Temperature and Moisture Content vs Inlet Pressure for Selected Simple and Bootstrap Cycle Concepts - Assumptions per Table 5

much heat transfer surface as concept D, but it also allows more ram-side pressure drop across the heat exchangers since it has more power available for the fan.

Unlike aircraft environmental control systems in which refrigeration is required to maintain the cabin and equipment at the desired temperatures, the IGG only requires refrigeration sufficient to bring the gas discharge temperature within the allowable temperature range (from 32° to 200°F) and to maximize the moisture removed prior to discharge into the tanks. In the cycles considered above, the discharge gas is at a very low temperature (relative to the allowable discharge temperatures), and consequently much of the cycle refrigeration potential is being used to provide cold gas and not to provide moisture removal. Thus, it appears worthwhile to consider alternate, or variant, cycle concepts in which most of the refrigeration is used for moisture removal, with the result that the gas is discharged at a higher temperature, but considerably lower moisture content than the basic simple and bootstrap cycles discussed above.

In these variant cycles (whether simple or bootstrap), the turbine discharge flow is used as the heat sink in a regenerator to further cool the gas prior to its expansion across the turbine. This additional cooling causes additional moisture to be condensed out before the gas is expanded. Figure 25 shows schematics of this addition to a cycle. In one part of the figure, all of the turbine discharge is passed directly through the regenerator; in the other part, the turbine discharge is mixed with a portion of the discharge from the regenerator by a jet pump. This flow recirculation is required to add sufficient heat to the turbine discharge to prevent it from freezing if it contains any condensed moisture and if its unmixed temperature is less than 32°F.

In these variant concepts, the water separator is eliminated by the addition of the regenerator. Thus, these cycles can show a weight advantage over concepts requiring a water separator for certain output flows. However, the main advantage is the improved moisture removal capability obtained by the addition of the regenerator. For example, at the assumed IGG design point, a simple cycle system having a precooler will provide gas having 124 gr/lb

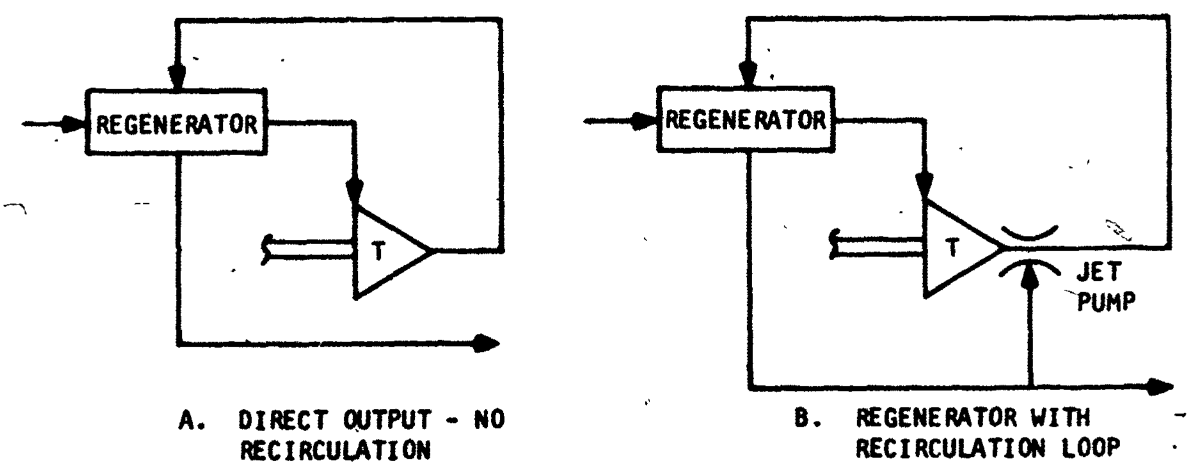


Figure 25. Regenerator Concepts

moisture at a temperature of 71°F; adding a regenerator with a recirculation loop (recirculation flow is twice output flow) and removing the water separator results in an output at 112°F having only 60 gr/lb moisture. Thus, the regenerator has reduced the output moisture by slightly more than a factor of 2 over that for a system without a regenerator.

The turbine output work for a regenerated cycle will be less than that for an unregenerated cycle because regeneration decreases the turbine inlet temperature. Thus, there will be less power available to drive the fan which is used to provide an airflow across the ran side of the heat exchangers while the aircraft is on the ground. This then either decreases the allowable heat exchanger ram-side pressure drop (hence, increasing heat exchanger size and weight) or requires a separately-driven ground cooling fan. Thus, although regeneration decreases the output moisture content, it results in a weight increase in all the cycle heat exchangers (or in a separate fan) in addition to the weight increase due to the regenerator itself.

Cycle Performance at Assumed Design Point

Figures 26, 27, 28, and 29 show the direct cooling, vapor cycle, and air cycle (both simple and bootstrap) concepts that have been considered for the IGG. In all concepts, ram air is passed through the heat exchangers (or condenser) prior to passing through the catalytic reactor; this minimizes the amount of ram air required. Table 6 gives the outlet temperature and moisture content for the various cycles for the assumed design point conditions. The data used in deriving the performance are shown in Table 7.

1. Direct Cooling

Neither of the direct cooling cycles, either catalytic reactor only (Figure 26A) or with a precooler (Figure 26B), can accomplish any moisture removal. Therefore, it will be necessary to combine the direct cooling techniques with the refrigeration techniques, or with the supplemental moisture removal techniques (sorbent beds) in order to obtain a low outlet moisture content.

2. Vapor Cycle

All three of the vapor cycle concepts shown in Figure 27 can meet the IGG performance requirements. The basic concept, Figure 27A, requires external drive power of about 1.2 kw/lb/min of inert output at 80 gr/lb moisture (see Figure 20 for approximate relation between compressor drive power and output moisture content). This is the only cycle in all the concepts considered that would require power in addition to that obtainable directly from the inert flow in the form of expansion. Neither the two-wheel or the three-wheel concepts have been analyzed due to the numerous iterations required to obtain a solution; however, both can easily meet the requirements. Because the cycle of Figure 27B does not have an integral ground cooling fan, whereas Figure 27C does, only Figure 27C will be further considered.

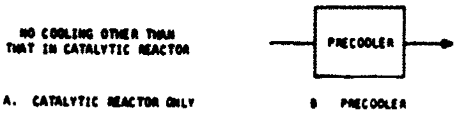


Figure 26. Direct Cooling Concepts

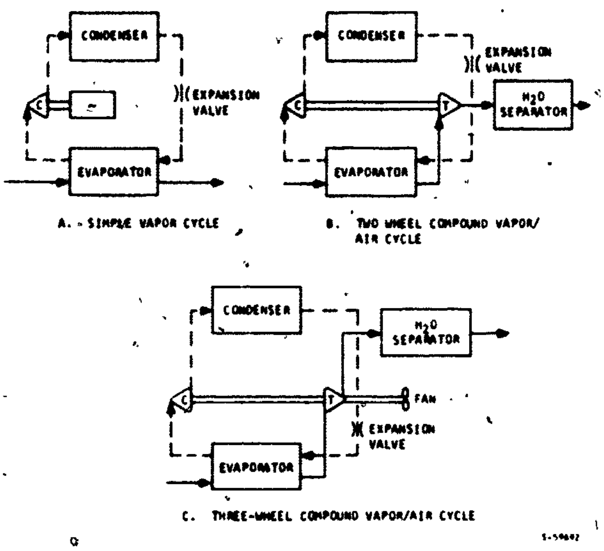


Figure 27. Vapor Cycle Concepts

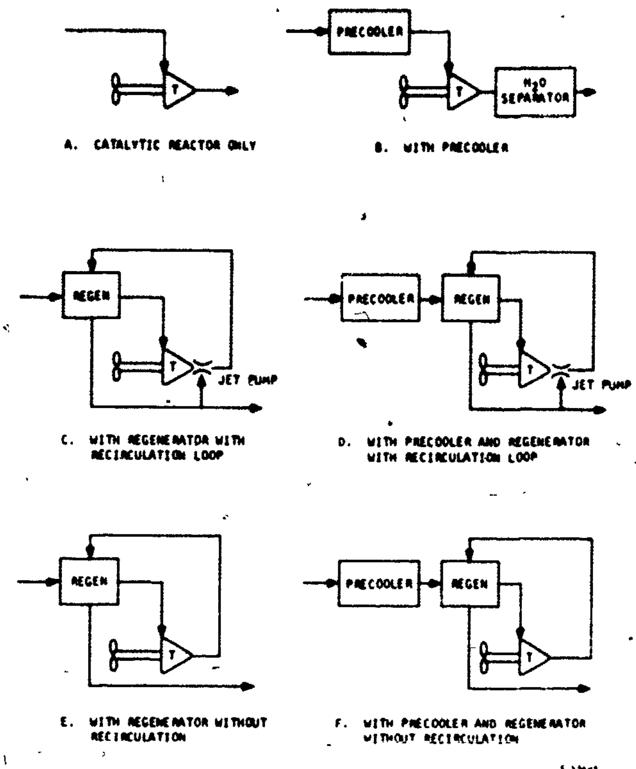


Figure 28. Simple Cycle Cooling Concepts

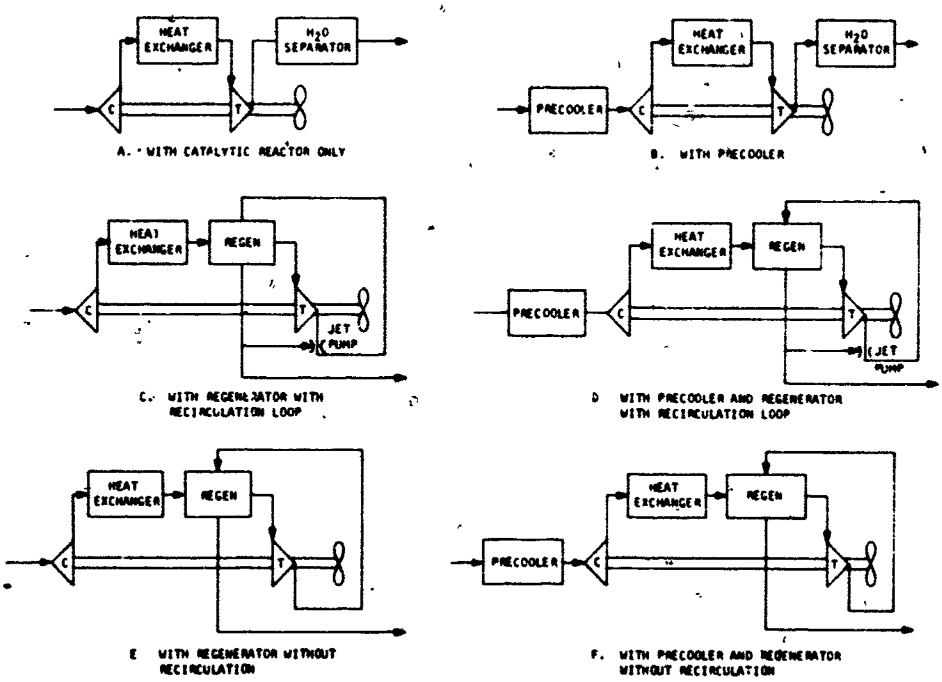


Figure 29. Bootstrap Cycle Cooling Concepts

TABLE 6

CYCLE PERFORMANCE COMPARISON*

Cooling Concept	Moisture Removal	Outlet Condition: Temperature, °F	Outlet Condition: Moisture, gr/lb Dry Inert
DIRECT COOLING			
Catalytic reactor only	No	323	611
Precooler	No	168	611
SIMPLE VAPOR CYCLE**	Yes	86.5 or less	80 or less
SIMPLE AIR CYCLE			
With catalytic reactor only	No	193	611
With precooler	Yes	71	124
With regenerator with recirculation loop	No	No need for recirculation since no freezing problem	
With precooler and regenerator with recirculation loop	Yes	112	60
With regenerator without recirculation	No	--	611
With precooler and regenerator without recirculation	--	Not feasible due to freezing at turbine outlet	
BOOTSTRAP CYCLE			
With catalytic reactor only	Yes	55	82
With precooler	Yes	32	42
With regenerator with recirculation loop	Yes	111	11
With precooler and regenerator with recirculation loop	Yes	111	11
With regenerator without recirculation loop	--	Not feasible due to freezing at turbine outlet	
With precooler and regenerator without recirculation	--	Not feasible due to freezing at turbine outlet	

*Assumptions as shown in Table 7.
**Requires 1.2 kw/lb/min unit at 80 gr/lb moisture, see Figure 20 for approximate relationship between power and moisture.

TABLE 7

ANALYSIS ASSUMPTIONS AT IGG DESIGN POINT

DESIGN POINT FOR COOLING EQUIPMENT	
Aircraft in idle descent at Mach 0.7, sea level, MIL-STD-210 hot day	
NOTE Higher airspeeds cause significant increases in the available bleed pressure to operate the equipment, therefore, making the system performance less critical.	
Bleed air at 35 psia, 425°F	
Ram air at 16.85 psia, 160°F, 182 gr/lb dry air (saturates at 102.5°F, 277 gr/lb dry air)	
AIR CYCLE COOLING EQUIPMENT PERFORMANCE	
Catalytic reactor output moisture	611 gr/lb dry inert
Ram air cooling flow	5 times inert flow
Catalytic reactor material temperature	1250°F maximum
Catalytic reactor effectiveness	0.85
Heat exchanger (precooler, regenerator, etc.) effectiveness	0.95 on controlling flow side
Compressor efficiency	0.78
Compressor pressure ratio	1.4
Turbine efficiency	0.82
Water separator efficiency	0.80
Jet pump discharge	2.0 times turbine flow for simple cycle systems
Jet pump discharge	2.5 times turbine flow for bootstrap cycle systems
All condensed moisture is sprayed into ram air to lower its temperature	
All component pressure drops ignored	
VAPOR CYCLE COOLING EQUIPMENT PERFORMANCE	
Condenser approach temperature	14°F
Evaporator approach temperature	7°F
Electric compressor drive efficiency	0.60
DISCHARGE CONDITION	
Pressure	15.7 psia (ambient +0.5 psia for distribution ducting pressure drop + 0.5 psig for desired tank pressure)
Temperature	32° to 200°F
Moisture as low as possible	

3. Simple Air Cycle

Of the simple air cycle concepts, only the simple cycle combined with a precooler and a regenerator with a recirculation loop (Figure 28D) can provide adequate moisture removal. The simple cycle with a precooler (Figure 28B) gives close to the desired outlet moisture condition (it provides 124 gr/lb instead of the desired 80 gr/lb moisture) and also will be considered further since its outlet moisture content can be lowered to the desired level by addition of a sorbent bed. Unfortunately, using improved components for the simple cycle with precooler, such as an 87 percent efficient turbine, a 97 percent effective precooler, and a 90 percent efficient water separator will only lower the output to 87 gr/lb moisture.

4. Bootstrap Air Cycle

Four of the bootstrap cycle concepts (Figure 29A through 29D) can meet or almost meet the desired outlet moisture content. However, the additional complexity of the bootstrap cycle (in comparison to the simple air cycle) is unwarranted if equivalent performance is obtainable with a simple cycle. Thus, only those concepts providing performance exceeding that obtainable with a simple cycle system should be considered further. This limits the bootstrap cycle concepts to those of Figure 29B (with precooler), Figure 29C (with regenerator with recirculation loop), and Figure 29D (with precooler and regenerator with recirculation loop).

However, the concept of Figure 29C in a three-wheel configuration does not have sufficient excess turbine power available to drive the fan if a 1.4 compressor pressure ratio is assumed. Thus, this concept must use a two-wheel bootstrap with a separately driven fan. Using a lower pressure ratio compressor to reduce the compressor power sufficiently to allow fan pressure rises equal to the 0.47 psia at sea level obtained by the concept of Figure 29C (having a precooler), results in output conditions having a higher moisture content than that obtainable with the simple cycle concept of Figure 28D.

5. Summary

In summary, the cycles that should be further considered are as follows:

- Direct cooling with precooler and sorbent bed, with ground cooling fan
- Simple vapor cycle, electrically or shaft-driven, with additional ground cooling fan to provide airflow across condenser and catalytic reactor
- Compound three-wheel vapor/air cycle with integral ground cooling fan
- Simple air cycle with precooler and sorbent bed
- Simple air cycle with precooler and regenerator with recirculation loop

- Three-wheel bootstrap air cycle with precooler

- Two-wheel bootstrap air cycle with regenerator with recirculation loop with separately-driven ground cooling fan

- Three-wheel bootstrap air cycle with precooler and regenerator with recirculation loop

Final selection of the best moisture removal cycle requires combining the information presented on the gas cooling concepts with that given on supplemental moisture removal concepts to obtain overall system performance requirements; this is presented at the end of this section.

SUPPLEMENTAL MOISTURE REMOVAL

Supplemental moisture removal concepts are required if the various gas cooling concepts can not provide adequate moisture control. The two classes of supplemental moisture removal that can be considered are:

- Water coalescer/separator--A device that coalesces condensed water fog into droplets that can be separated out of the process flow

- Sorbent beds--Packed beds containing a desiccant material to dry the process flow

The water separator is only effective where the inlet flow contains condensed moisture (relative humidity greater than 100 percent); the sorbent beds can provide moisture removal for inlet relative humidities both above and below saturation.

For the IGG application, the water separators can be used on the discharge flow from expansion turbines. The cycles considered for gas cooling included water separators on the turbine discharge of those cycles in which the flow contained condensed moisture.

The sorbent beds can be used on the discharge flow from all of the gas cooling cycles considered previously; however, their best performance is obtained when the inlet flow is at a relatively low temperature.

Water Separators/Coalescers

In general, the water discharged from a turbine consists of very fine mist having a drop size varying from 0.1 to 1×10^{-6} in. The drop size for a particular turbine is directly dependent upon the turbine discharge pressure and is inversely proportional to the rate at which the expansion occurs. For aircraft use, it is desirable to minimize the weight of the turbine, so that the expansion rate is normally quite high, thus, the drop size approaches 0.1×10^{-6} in. This size is far too small to allow centrifugal separation of the droplets

from the inert flow. Tests at AiResearch Manufacturing Company have indicated that centrifugal separators having gravity fields as high as 2000 g's produce little or no separation of droplets at sizes below about 5×10^{-6} in. Gravity fields this high require substantial flow velocities, resulting in large pressure drops across the separator. Drop sizes of 50 to 100×10^{-6} in. are required before the separation velocities are lowered to a reasonable level. Thus, it is necessary to merge the small droplets at the turbine discharge into larger droplets prior to passing them into a centrifugal separator (ideally a series of swirled vanes in the flow stream).

There are two practical ways in which the droplet size may be increased:

- Coagulation--Allow the droplets to merge into larger drops naturally by joining together as they collide with one another in the flow stream.

- Coalescence--Provide an artificial surface on which the droplets can impact and run together into larger drops; they will be blown off the surface when the accumulated moisture is such that the combined drag and gravity forces offset the surface tension effects of the small drops.

Either of these ways will accomplish the desired effect; however, coagulation requires a considerable length of duct between the turbine discharge and the centrifugal separator. This can best be understood by recognizing that 1000 1×10^{-6} in. droplets must impact with one another to coagulate into 10×10^{-6} in. drop; the time for this process to occur can be translated directly into required combinations of duct length and flow velocities between the turbine discharge and the centrifugal separator. Consequently, the preferred method for aircraft environmental control systems is to utilize a coalescer bag which provides an artificial surface for coalescence.

Coalescer bags consist of a random mesh of fine threads having numerous very fine dentriles, or nap, protruding from the thread. It is this nap surface that accomplishes the moisture coalescence. However, this surface is susceptible to blockage by dirt or foreign particles in the process flow so that it becomes necessary to periodically replace the coalescer bag. This is a relatively minor maintenance item, and the bag replacement cost is low.

The overall efficiency of the coalescer/separator unit is primarily dependent upon the ability of the bag to coalesce all of the incoming moisture into drops large enough to be handled by the centrifugal separator. Some of the incoming moisture does not coalesce into adequately-sized drops so that the separator output still contains entrained moisture. Coalescer efficiencies of about 90 percent have been obtained; however, 80 percent is a more realistic efficiency over the life of the coalescer bag.

It should be noted that moisture removal can be accomplished with nearly 100-percent efficiency by condensing within a heat exchanger. Thus, it is preferable to use cycles having heat exchanger condensation rather than turbine condensation with water separation if a low output moisture content is desired.

Sorbent Beds

Sorbent beds can be divided into two classes: direct flow and regenerable. In direct flow beds all of the process flow passes through a single bed which is sized for a given interval between replacement, or on-ground regeneration. In regenerable beds, two beds are used with the flow alternating between the two; one bed is removing moisture from the process stream while the other is being regenerated. Regeneration can be accomplished by heating the bed to drive out the water, by reducing bed pressure and using a part of the dried gas to flow through the bed to absorb the water, or by a combination of both processes.

1. Sorbent Material Selection

Table 8 lists the sorbent materials that appear attractive for the IGG application. In comparing the drying agents, four specific characteristics are of importance: (1) stability of water loading with operating temperature, (2) high water-loading capacity at low water-vapor partial pressure, (3) total water-holding capacity, and (4) a low heat of reaction. Based on these criteria, 13-X molecular sieve and silica gel are the optimum materials.

TABLE 8

SORBENT CHARACTERISTICS

Material	Heat Released per lb Water, Btu	Remarks
Boric acid	1400	Low dynamic removal efficiency*
Calcium chloride	1440	Low dynamic removal efficiency*
Calcium sulfate	1700	Many liquid solution phases*
Lithium chloride	1480	Low dynamic removal efficiency*
Potassium hydroxide	2290	Bed caked*
Molecular sieve 13-X	1425	High dynamic removal efficiency
Silica gel	1450	High dynamic removal efficiency

*Based on American Cyanamid report AFAPL-TR-69-68

Both silica gel and 13-X mol sieve are commonly used in life support systems for atmospheric gas processing, and they have been specifically developed as industrial drying agents which exhibit stability with temperature variations and are not subject to caking. Also, both materials can be easily regenerated without degradation.

Figure 30 compares the water-holding capacity of silica gel with that of molecular sieve. The data show that the water-holding capacity of silica gel is greatly affected by operating temperature, particularly at high water partial pressure. The 13-X material exhibits a relatively small water-holding change with temperature. Based on these data, molecular sieve provides a lower weight sorbent bed for low inlet water pressures than does silica gel; on the other hand, silica gel provides superior performance at water pressures exceeding 5 to 10 mm Hg. Figures 31 and 32 give detailed test data on the water-loading performance for silica gel and molecular sieve; the data in these figures have been used as the basis for determining the sorbent bed weight.

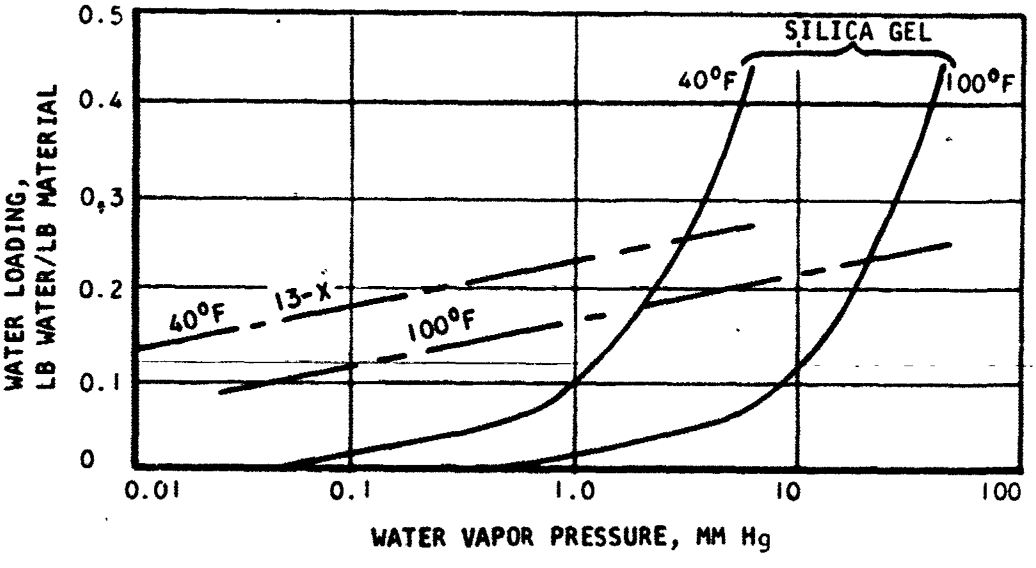


Figure 30. Sorbent Characteristics Comparison

2. Direct Flow Beds

Figure 33 shows the weight of both silica gel and 13-X molecular sieve beds required to provide an outlet moisture content of 80 and 20 gr/lb. The data assume that the inlet gas is saturated with moisture. Clearly, molecular sieve provides better performance at the higher inlet temperatures and silica gel is best at the lower temperatures.

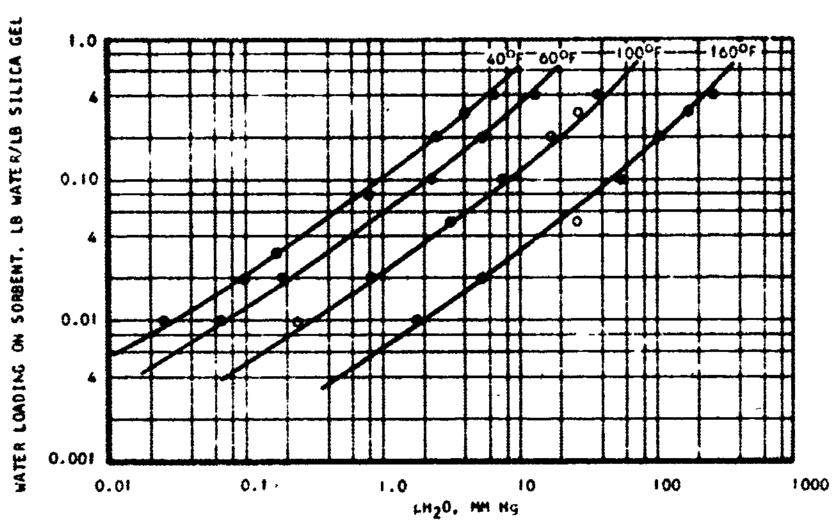


Figure 31. Silica Gel Water-Loading Data

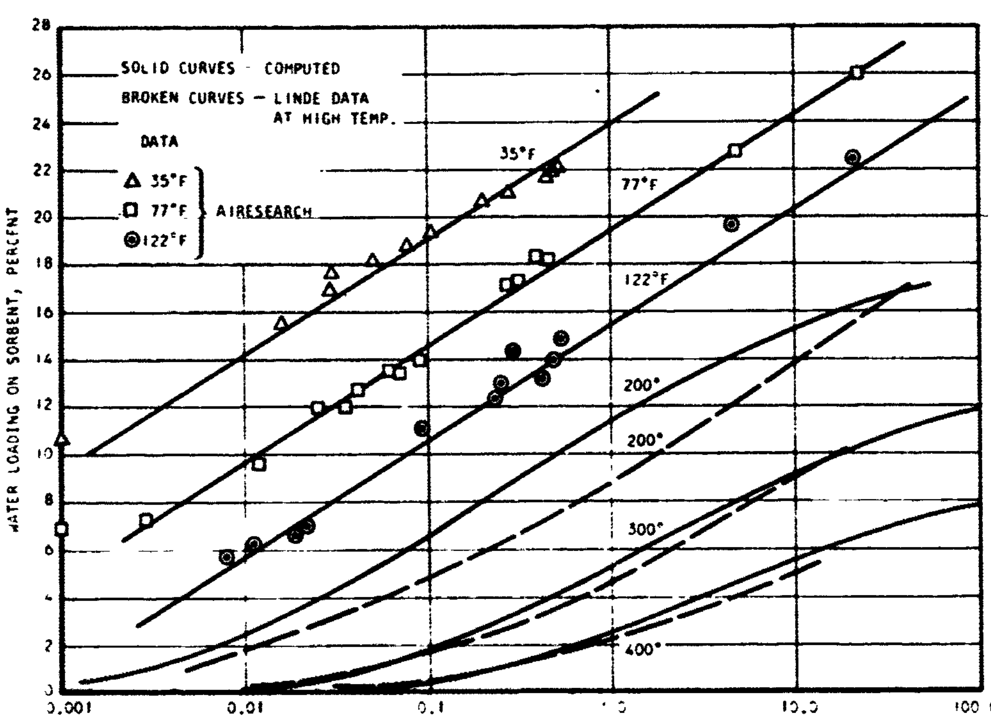


Figure 32. 13-X Molecular Sieve Water-Loading Data

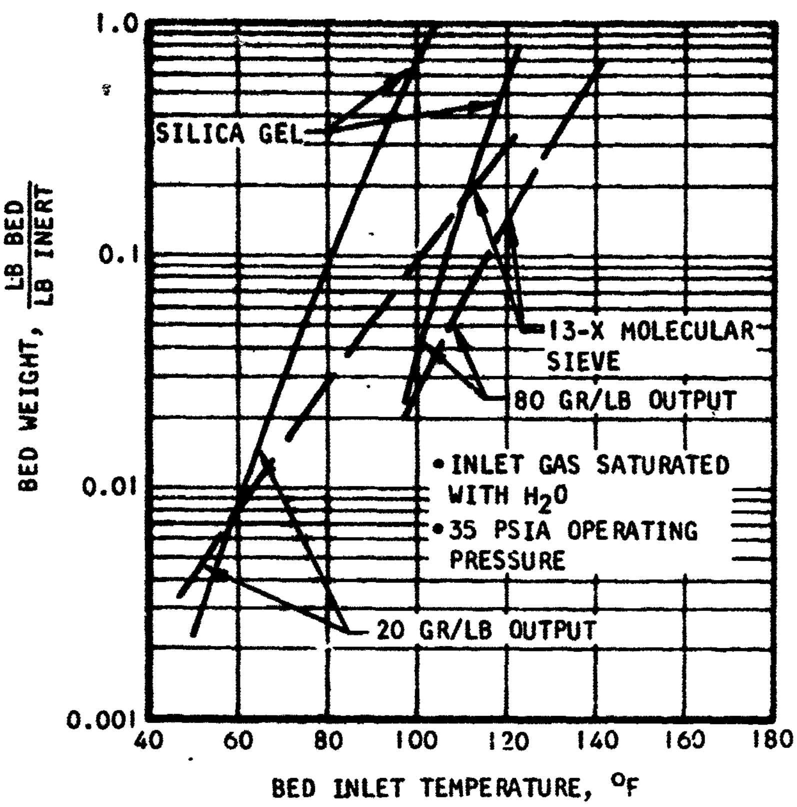


Figure 33. Direct Flow Bed Sorbent Weight

Because substantial heat is released to the process flow as moisture is absorbed, ~~it becomes~~ necessary to provide bed cooling for inlet temperatures exceeding about 114°F (saturated at 186 gr/lb at 35 psia) if the outlet is to be maintained below 200°F and 80 gr/lb moisture or less. Thus, sorbent beds, whether direct flow or regenerative, are limited to reasonably low inlet moisture contents (in comparison to the moisture content at the catalytic reactor outlet) if they are to be operated without a bed cooling system. Consequently, it is essential to provide moisture removal and gas cooling between the catalytic reactor output and the sorbent bed inlet.

The weight data on Figure 33 exclude an allowance for the bed structure and control valving. However, the data indicate that there is a substantial weight associated with a direct flow sorbent bed. For example, a bed designed for replacement or regeneration after processing 1000 lb of inert would weigh about 175 lb based on an inlet of 35 psia and 90°F and an outlet of 80 gr/lb.

3. Regenerable Beds

It is possible to reduce the amount of sorbent material and to eliminate the need for sorbent replacement if regenerable beds are used. These beds, as shown in Figure 34, operate in a cyclic mode in which one bed is absorbing water while the other is being desorbed. For desorption, a portion of the processed flow (dried inert) is passed through the desorbing bed at a reduced pressure.

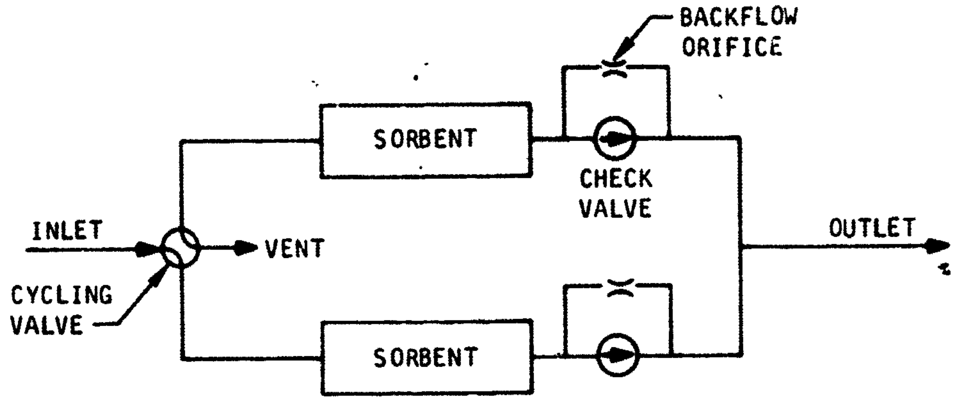


Figure 34. Regenerable Sorbent Bed Schematic

The regenerable concept as shown is similar to that patented by C. W. Skarstrom of Esso. The performance data for this concept have been calculated by AiResearch, but they indicate performance consistent with that predicted by Esso.

Figure 35 shows the sorbent bed weight as a function of the inert inlet temperature assuming that the inlet flow is saturated with water. The data indicate that the sorbent weight is considerably less than that required for direct flow sorbent beds; additionally, the temperature increase across the bed is almost negligible (about 5°F) since the beds are operating in a transient state. However, a significant portion of the bed flow is used to regenerate the desorbing bed. For the conditions shown (35 psia inlet pressure, 14.7 psia desorbing pressure), 0.38 lb of dried inert must be passed through the desorbing bed and vented to ambient for every 1 lb of inert input to the beds. Thus, it is necessary to input about 1.6 lb of inert for every 1 lb out of the beds. Consequently, it will be necessary to use larger catalytic reactor and gas cooling equipment with concepts employing regenerable sorbent beds.

It is possible to reduce the amount of flow used for regeneration by reducing the desorbing pressure. For example, at 5 psia desorbing pressure, the beds would only require about 1.15 lb inert/lb output. However, at the assumed design point, this would require a vacuum pump on the discharge line.

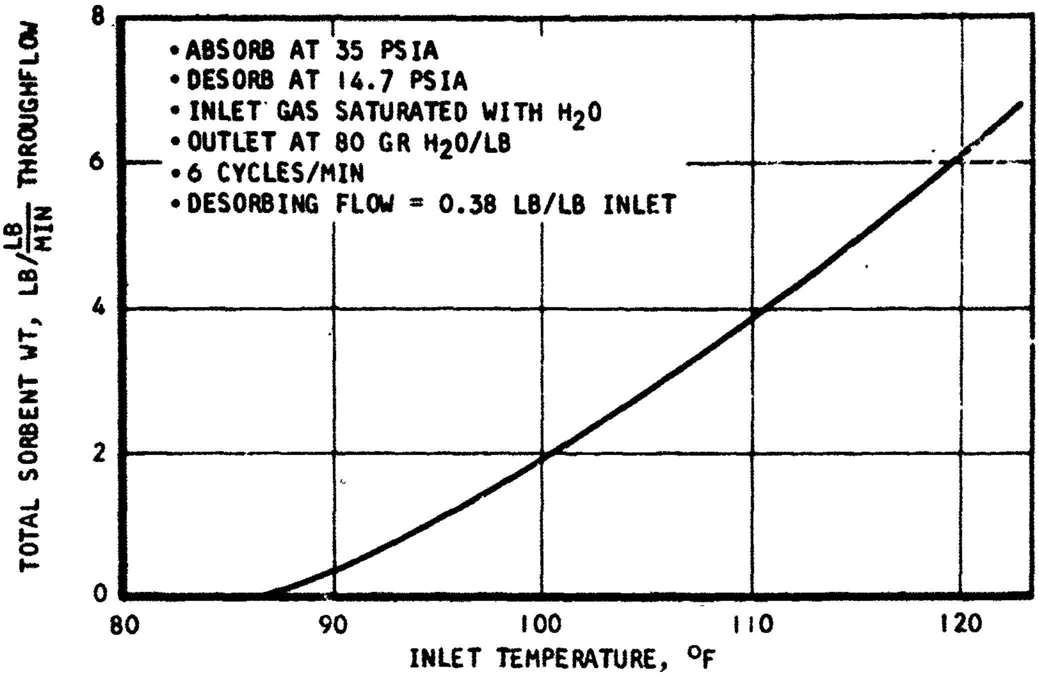


Figure 35. Regenerable Sorbent Bed Weight S-59700

SYSTEM SYNTHESIS AND SELECTION

The studies of the inert gas source, gas cooling and moisture removal, and supplemental moisture removal concepts have served to reduce the number of techniques that are acceptable for the IGG application. In particular, these studies have narrowed the candidate concepts to the following:

- Inert gas sources

    Ram air-cooled catalytic reactor

- Gas cooling and moisture removal

    Direct cooling with precooler and sorbent bed, with ground-cooling fan

    Simple vapor cycle, electrically or shaft-driven, with ground-cooling fan

    Compound three-wheel vapor/air cycle with integral ground-cooling fan

    Simple air cycle with precooler and sorbent bed

    Simple air cycle with precooler and regenerator with recirculation loop

Three-wheel bootstrap air cycle with precooler

Two-wheel bootstrap air cycle with regenerator with recirculation loop with ground-cooling fan

Three-wheel bootstrap air cycle with precooler and regenerator with recirculation loop

- Supplemental moisture removal techniques

  Water separators (included in gas-cooling concepts, where necessary)

  Direct flow sorbent beds

  Regenerable sorbent beds

Since catalytic reactors have been found to be the only competitive inert gas source, it is possible to establish the optimum system configuration by confining all further tradeoffs to the gas-cooling and moisture removal concepts and supplemental moisture removal concepts.

Selection Criteria

The criteria used to select the inerting system are as follows:

- Performance--moisture removal, temperature, and efficiency (lb bleed/lb inert)
- Weight
- Reliability
- Maintainability
- Cost

1. Performance

Since all concepts use the same inert gas source, their gas composition is identical. However, the moisture level and the temperature of the inert into the tanks are different for each concept. It is essential that each concept meet the specification moisture (less than 80 gr/lb) and temperature (between 32° and 200°F) requirements at the assumed design point; thus, some concepts require sorbent beds to reduce the moisture content to the desired level. However, within the acceptable moisture/temperature envelope, there is little incentive for improved performance. Lower moisture contents represent an advantage, but the desired level has been selected such that fuel gaging, tank bacteria growth, or other water associated problems would not occur. A slight advantage of low moisture contents is that they reduce the amount of acid (such as H_2SO_3) delivered to the tanks.

Another indicator of the concept performance is the cycle efficiency in terms of total bleed flow, or bleed flow and electric power, required to operate the cycle. Some cycles use ground-cooling fans and compressors that must be driven from an external power source, either electrically or pneumatically. Thus, their efficiency (measured in bleed quantity necessary to generate 1 lb inert, for an all-pneumatic drive) is less than that for concepts requiring no external power. The concepts using regenerable sorbent beds vent a portion of the flow in order to accomplish regeneration; thus, the bleed requirements for such systems are increased also.

2. Weight

There are strong incentives to minimum system weights for high-performance military aircraft. High subsystem weights reduce either the range or the payload of the aircraft. System weight includes both the fixed weight of the components, and the weight of the fuel required to operate the system. The fuel weight, in turn, is made up of three quantities:

- Fuel used by the reactor to generate the inert gas
- Fuel used by the engine to provide bleed air to the inerting system
- Fuel used by the engine to offset the additional drag imposed by using ram air to cool the inerting system heat exchangers

For evaluation purposes, it is assumed that the aircraft will fly the typical missions defined in Section 4 of the inerting system specifications. Additionally, it is assumed that at least three missions (six refuelings) must be flown between direct flow sorbent bed replacement. Estimates of fuel weight penalty are dependent upon the details of the system operation, and hence are not included in this section.

3. Reliability

Although the inerting system will be used throughout the flight, its operational status is not essential to mission performance. Loss of the inerting system is highly undesirable, but it in itself does not cause any reduction in performance capability; performance reduction only occurs if the inerting system is inoperative and if the fuel tanks are subjected to a condition that will cause a tank fire.

4. Maintainability

Inerting systems can be justified for military aircraft since their installation should increase the effective fleet size by reducing losses in action. However, the maintainability of the inerting system is important since the maintenance requirements of the system could tend to increase the amount of aircraft down-time (thereby reducing the effective fleet size).

Unscheduled maintenance actions are a function of the system reliability; the time to perform the action is dependent upon the system configuration, the location on the aircraft, etc. Assuming equivalent configurations for the various systems, the reliability indicates their relative unscheduled maintenance time. Scheduled maintenance, on the other hand, is primarily dependent upon the life capabilities of the various system components. Of the gas cooling and moisture removal components, only the water separator and the direct flow sorbent beds will have high scheduled maintenance requirements. The water separator will require periodic replacement of the coalescer bag, and the sorbent bed material will require periodic replacement or regeneration.

5. Cost

For military combat aircraft, there is a strong incentive to optimize performance; thus, cost is generally only an important selection criterion when two candidate systems are approximately equivalent in the various classifications listed above. For the inerting system, the bulk of the cost will be in the system controls and the catalytic reactor; components common to all candidate concepts.

6. Weighting Factors

The following weighting factors have been used to evaluating the various cooling and moisture removal concepts:

- Performance 1.0
- Weight 1.0
- Reliability 0.6
- Maintainability 0.8
- Cost 0.6

It should be noted that reliability itself is not as important as is maintainability since inerting system operation is not critical to successful mission performance. However, when considered together, the weighting factor given to reliability/maintainability (1.4) indicates that this is the most important design selection criterion.

An alternate method of establishing the optimum concept is to perform the rating on the basis of three levels of criteria:

- Absolute Criteria--Certain minimum criteria that must be met if the concept is to be considered--for the IGG, the only absolute criteria are the performance criteria concerning moisture content, temperature, and gas composition of the inerted gas

- Highly Desirable Criteria--The reliability/maintainability and weight of the inerting system are the most important parameters governing inerting concept selection for concepts having comparable performance. (Note that weight includes weight penalty attributable to fuel required to generate bleed air and to offset ram air drag.)

- Desirable Criteria--Additional criteria that are desirable, but of lesser importance are the volume of the inerting system and its cost

This tiered-criteria concept is reflected in the weighting factors assigned to the various selection criteria. It is additionally reflected in the fact that several of the candidate concepts are eliminated from further consideration when the quantitative data show excessive weight and volume, or inability to meet the minimum performance criteria.

Concept Quantitative Data

Table 9 summarized the quantitative data for each of 11 cooling and moisture removal concepts. Previous analyses of the gas cooling and moisture removal concepts and of the supplemental moisture removal concepts have served to reduce the candidate concepts to the 11 shown in the table. The data shown indicate that the direct cooling concepts, Concepts I and II, can be eliminated as inerting system candidates due to inability to meet the minimum performance criteria (Concept I) and excessive weight (Concept II).

1. Performance

The moisture and temperature performance data are those of Table 7, modified by the effects of adding sorbent beds as required. The bleed air usage data are based on using the ground cooling fan for 10 percent of the delivered flow (fan requires about 0.4 lb bleed/lb inert), on requiring about 1.7 lb bleed/lb inert to power a Freon compressor if pneumatically driven (about 1.2 kw [illegible] r electric drive), and on losing 38 percent of gas put through regenerable sorbent beds.

The data indicate that all concepts except Concept I can meet the minimum moisture content and temperature requirements at the assumed design point. Additionally, calculations at other operating points, such as ground operation or subsonic cruise, indicate that all concepts can provide lower moisture contents at those operating conditions.

2. Weight

Tables 10 and 11 give fixed weight breakdowns for each of the candidate concepts for the TFA and B-1 aircraft. The tables include the catalytic reactor, ducting, fire insulation, and system controls weights (gas distribution lines and valving on the tanks are excluded). The data are based on the component weight vs inert flow graphs shown in Figures 36 through 46. Table 11 assumes that the catalytic reactor is sized for the maximum emergency descent flow of 200 lb per min. Later studies indicate that the emergency descent flow can bypass the reactor, thus reducing the reactor size.

TABLE 9

COOLING AND MOISTURE REMOVAL CONCEPT QUANTITATIVE DATA

	Cooling and Moisture Removal Concept	External Drive Power	Number of Major Components	Performance gr H_2O/lb	Performance Temp, °F	Bleed Air Usage (4) lb Bleed/lb Inert	Fixed (3) Weight, lb B-1	Fixed (3) Weight, lb TFA	High-Maintenance Components	MTBF, (5) Equipment Operating, hr
I	Direct cooling with precooler, direct flow sorbent bed, ground cooling fan	Turbofan	5	80 (2)	601	1.09	Noncompetitive		Sorbent Bed	10,200
II	Direct cooling with precooler, regenerable sorbent bed, ground cooling fan	Turbofan	6	80 (2)	173	1.72	over 1800	over 1000	-	6,900
III	Simple vapor cycle, electric-drive, ground cooling fan	Freon Compressor, Turbofan	6	80 (1)	86.5 (1)	1.09 plus 1.2 kwe/lb inert	486	136	-	6,450
IV	Simple vapor cycle, pneumatic-drive, ground cooling fan	Freon Compressor, Turbofan	6	80 (1)	86.5 (1)	2.79	451	125	Compressor Seal	1,590
V	Compound three-wheel vapor/air cycle	-	6	80 (1)	62 (1)	1.05	421	119	Compressor Seal	1,785
VI	Simple air cycle with precooler, direct flow sorbent bed	-	6	80 (2)	107	1.05	573 (3)	149 (3)	Water Separator, Sorbent Bed	14,600
VII	Simple air cycle with precooler, regenerable sorbent bed	-	7	80 (2)	76	2.28 (6)	800	299	Water Separator	8,700
VIII	Simple air cycle with precooler, regenerator with recirculation loop	-	5	60	112	1.05	755	209	-	16,200
IX	Three-wheel bootstrap air cycle with precooler	-	7	42	32	1.05	581	196	Water Separator	12,500
X	Two-wheel bootstrap air cycle, regenerator with recirculation loop, ground cooling fan	Turbofan	6	11	111	1.09	1153	324	-	7,070
XI	Three-wheel bootstrap air cycle with precooler and regenerator with recirculation loop	-	7	11	111	1.05	1343	386	-	15,000

(1) Lower moistures and temperatures obtainable by using more external drive power.
(2) Lower moistures, but higher temperatures obtainable by increasing sorbent bed weight.
(3) Based on steel HX and sorbent bed requiring replacement every 3 missions.
(4) Based on 10 percent of total inert flow used while aircraft is on ground.
(5) MTBF data only consider major cooling/moisture removal components, controls and catalytic reactor excluded.
(6) Includes bleed losses in regenerable bed and bleed to drive vacuum pump on bed discharge line.

TABLE 10

INERTING CONCEPT WEIGHT SUMMARY FOR TFA AIRCRAFT*

Component	Gas Cooling and Moisture Removal Concept										
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Catalytic Reactor	20	35	20	20	20	20	35	20	20	20	20
Inert/Air Precooler	45 12	75 22	-	-	-	45 12	75 22	45 12	46 15	-	46 15
Inert/Fuel Precooler	8 3	12 4	-	-	-	8 3	12 4	8 3	8 3	-	8 3
Inert/Air Heat Exchanger	-	-	-	-	-	-	-	-	49 15	42 15	49 15
Inert/Fuel Heat Exchanger	-	-	-	-	-	-	-	-	7 3	7 3	7 3
Regenerator	-	-	-	-	-	-	-	80 50	-	195 95	195 95
Freon Evaporator	-	-	9	9	9	-	-	-	-	-	-
Freon/Air Condenser	-	-	15	15	15	-	-	-	-	-	-
Freon/Fuel Condenser	-	-	5	5	5	-	-	-	-	-	-
Simple Cycle ACM	-	-	-	-	-	14	21	14	-	-	-
Bootstrap Cycle ACM	-	-	-	-	-	-	-	-	19	8	19
Freon Compressor and Accumulator	-	-	35	24	18	-	-	-	-	-	-
Ground Cooling Turbofan	7	10	7	7	-	-	-	-	-	7	-
Water Separator	-	-	-	-	5	5	8	-	5	-	-
Sorbent Beds	Very large	Over 900	-	-	-	15	100	-	-	-	-
Controls and Valving	25	31	28	28	25	25	31	25	25	28	25
Ducting and Miscellaneous	-	-	17	17	17	17	17	17	7	17	17
Total Weight, lb	Very large	Over 1060	136	125	119	149 111	[illegible] 258	209 121	196 122	324 193	386 212

*Numbers in parenthesis are for aluminum heat exchangers

TABLE 11

INERTING CONCEPT WEIGHT SUMMARY FOR B-1 AIRCRAFT*

Component	Gas Cooling and Moisture Removal Concept										
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Catalytic Reactor	185	185	185	185	185	185	185	185	185	185	185
Inert/Air Precooler	152 48	255 78	-	-	-	152 48	255 78	152 48	160 53	-	160 53
Inert/Fuel Precooler	23 7	32 10	-	-	-	23 7	32 10	23 7	23 7	-	23 7
Inert/Air Heat Exchanger	-	-	-	-	-	-	-	-	165 55	150 50	165 55
Inert/Fuel Heat Exchanger	-	-	-	-	-	-	-	-	17 5	17 5	17 5
Regenerator	-	-	-	-	-	-	-	280 105	-	670 310	670 310
Freon Evaporator	-	-	25	25	25	-	-	-	-	-	-
Freon/Air Condenser	-	-	50	50	50	-	-	-	-	-	-
Freon/Fuel Condenser	-	-	15	15	15	-	-	-	-	-	-
Simple Cycle ACM	-	-	-	-	-	23	32	23	-	-	-
Bootstrap Cycle ACM	-	-	-	-	-	-	-	-	31	13	31
Freon Compressor and Accumulator	-	-	93	58	46	-	-	-	-	-	-
Ground Cooling Turbofan	22	22	22	22	-	-	-	-	-	22	-
Water Separator	-	-	-	-	8	8	11	-	8	-	-
Sorbent Beds	Very large	over 1600	-	-	-	90	185	-	-	-	-
Controls and Valving	38	46	42	42	38	38	46	38	38	42	38
Ducting and Miscellaneous	54	54	54	54	54	54	54	54	54	54	54
Total Weight, lb	Very large	over 1800	486	451	421	573 453	800 601	755 460	581 436	1153 686	1343 738

*Numbers in parentheses are for aluminum heat exchangers

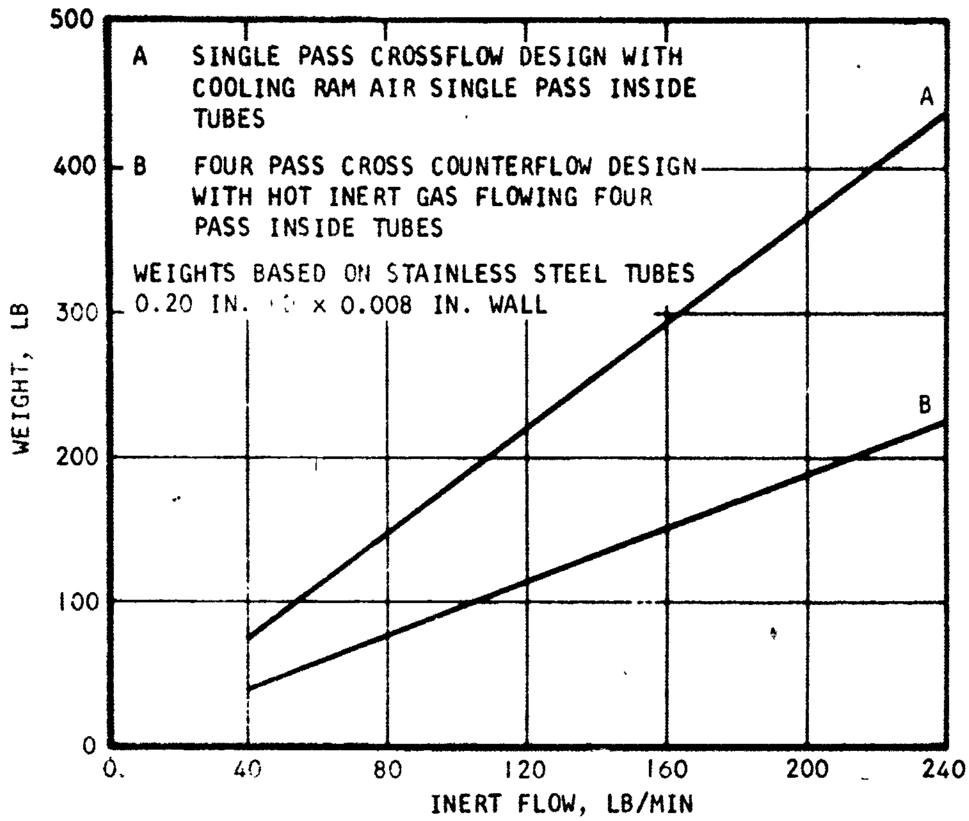


Figure 36. Ram Air-Cooled Catalytic Reactor Weight

The data on sorbent beds given earlier in Figures 33 and 35 indicate that there is a large weight penalty attributable to operating the beds at elevated inlet temperatures. Thus, the sorbent bed weights for Concept I are so large as to be outside of the available data; thus, Concept I can be eliminated from further consideration.

Similarly, for Concept VII, it is necessary to add a vacuum pump on the regenerable bed discharge line to provide some means of lowering the bed pressure during regeneration. It should be noted that this concept has reduced the pressure inlet to the bed to about 16 psia, in comparison to the 35 psia at which bleed air is assumed to be available at the design point.

For the TFA aircraft, the components are all sized for the maximum flow capability of the system, 20 lb/min. For the B-1 aircraft, the cooling components are sized for the maximum normal operation flow requirement of 67 lb/min since the emergency descent flow is obtained by bypassing the gas cooling and moisture removal equipment, routing the flow directly from the catalytic reactor into the fuel tanks. Additionally, for the concepts using regenerable sorbent beds, the components upstream of the beds have been sized for 1.6 times the required flows. The direct flow sorbent beds are sized for three typical missions without replacement; thus, the TFA beds are sized for 210-lb throughflow, the B-1 for 1890-., throughflow. It should be noted that the typical missions defined in the inerting system specifications (Appendixes A and B) have inflight refueling; thus, the sorbent beds are sized for about six aircraft refuelings. These bed sizes exclude the effects of gas flows required for fuel scrubbing.

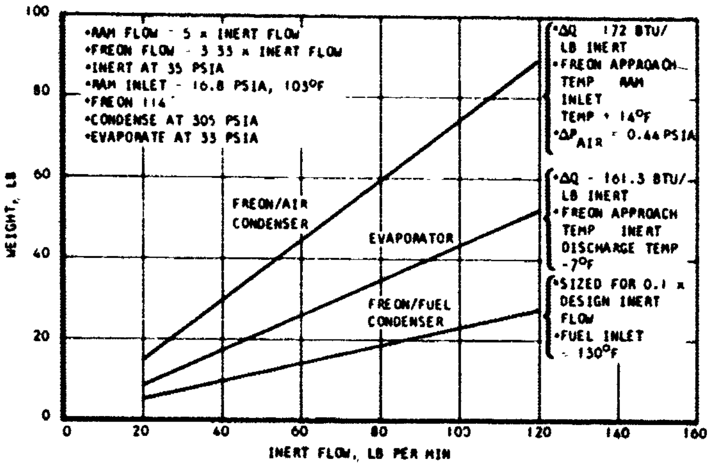


Figure 37 Vapor Cycle Heat Transfer Surface Weight

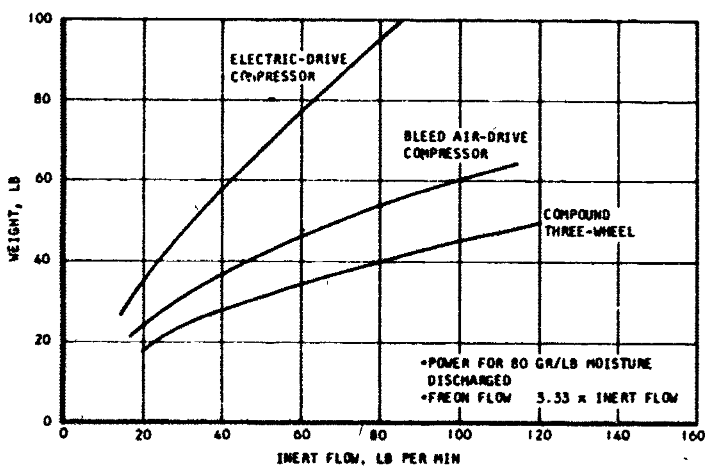


Figure 38. Vapor Cycle Rotating Equipment Weight

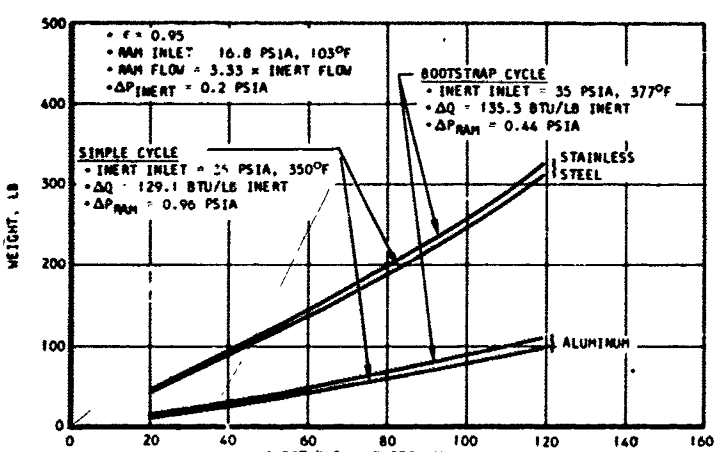


Figure 39 Inert/Ram Air Precooler Weight

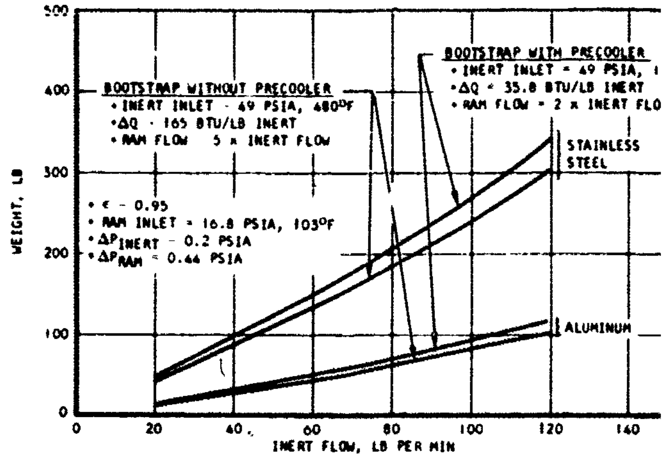


Figure 40. Inert/Ram Air Heat Exchanger Weight

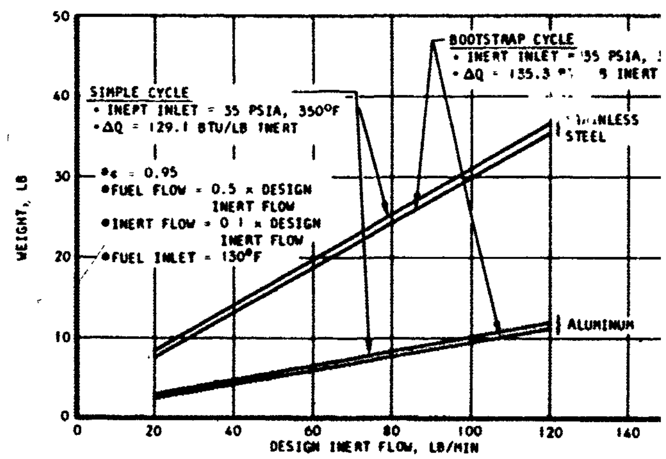


Figure 41. Inert/Fuel Precooler Weight

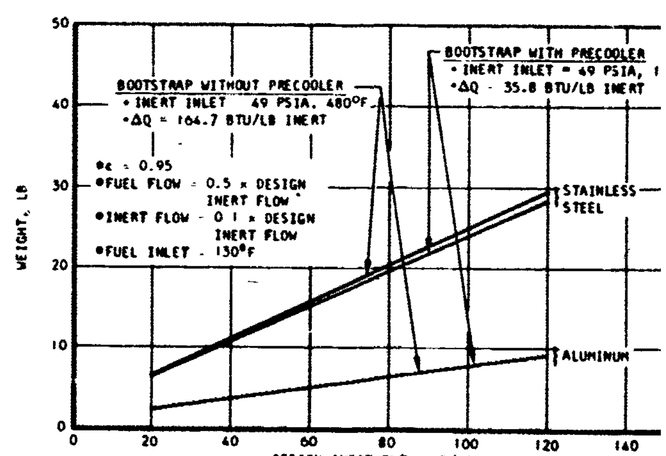
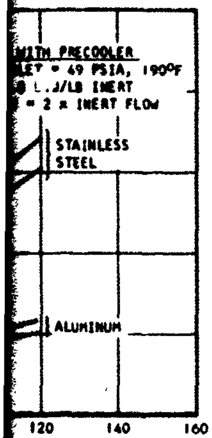
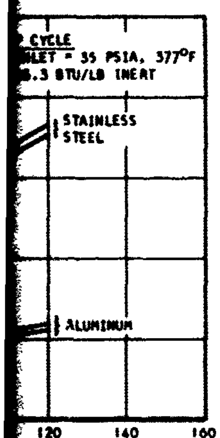


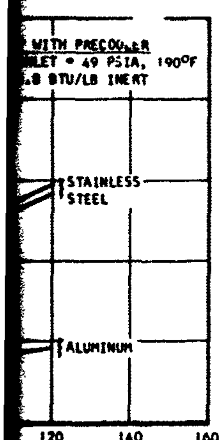
Figure 42. Inert/Fuel Heat Exchanger Weight



ght



ght



cr Weight

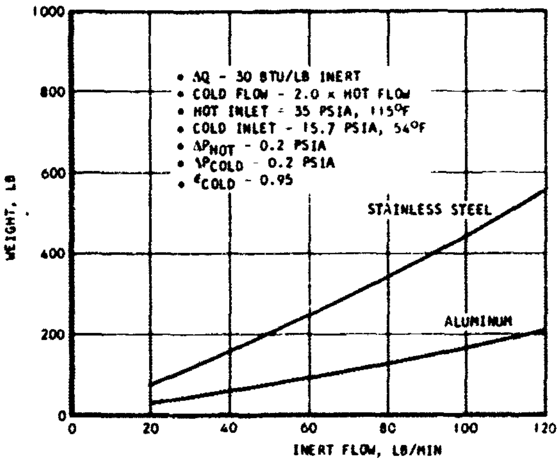


Figure 43. Regenerator Weight for Simple Cycle

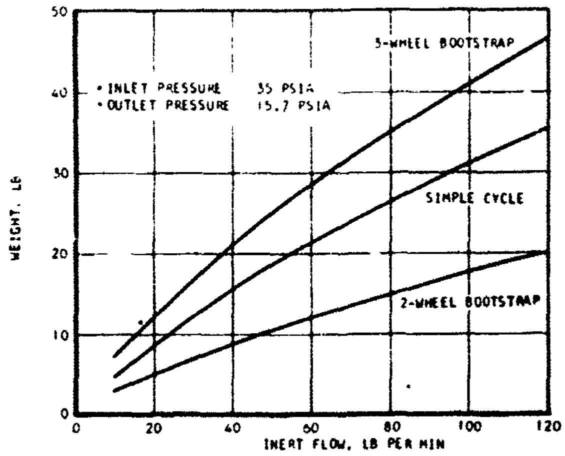


Figure 45. Air Cycle Rotating Equipment Weight

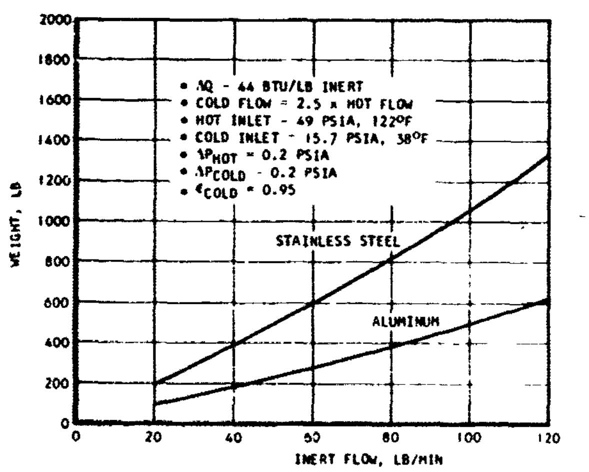


Figure 44. Regenerator Weight for Bootstrap Cycle

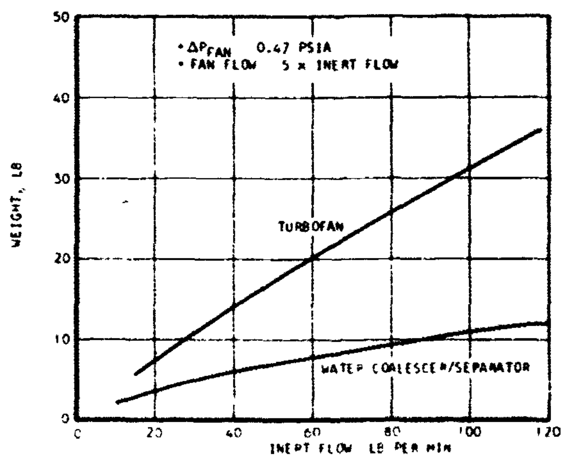


Figure 46 Turbofan and Water Separator Weight

L-6184

2

3. Reliability

The reliability data given in Table 9 for each concept only consider the major cooling and moisture removal components. A more detailed analysis would indicate that most of the inerting system failures are attributable to the ancillary components, such as valves, controls, etc. The data are based on the component MTBF information shown in Table 12. These MTBF's are indicative of 1970 best practice design.

TABLE 12

SELECTED COMPONENT RELIABILITY DATA

Compnent	MTBF, Equipment Operating hr	Failure Rate $\times 10^{-6}$ hr	Component	MTBF, Equipment Operating hr	Failure Rate $\times 10^{-6}$ hr
Inert/air precooler	200,000	5	Freon/fuel condenser	100,000	10
Inert/fuel precooler	100,000	10	Shaft-driven Freon compressor	20,000	500
Simple cycle ACM	25,000	40	Electric motor-driven Freon compressor	40,000	25
Two-wheel bootstrap ACM	25,000	40	Three-wheel Freon rotating unit	2,000	500
Three-wheel bootstrap ;	25,000	40	Water separator	100,000	10
Inert/air heat exchanger	200,000	5	Turbofan	25,000	40
Inert/fuel heat exchanger	100,000	10	Turbofan shutoff valve	25,000	40
Regenerator	150,000	6 7	Direct flow sorbent bed	300,000	3.3
Freon evaporator	50,000	20	Regenerative sorbent beds	20,000	50
Freon/air condenser	50,000	20			

Concept Evaluation Matrix

Table 13 presents an evaluation matrix for the candidate concepts, showing the relative ratings for each concept for each of the five selection criteria. The total, weighted rating for each concept combines the individual ratings according to the weighting parameters described previously.

Based on this information, the optimum catalytic reactor inerting concept for both the TFA and B-1 aircraft consists of a ram air-cooled catalytic reactor supplying inert flow to a precooler, followed by a simple air cycle using a regenerator with a recirculation loop. Figure 47 shows a simplified schematic of the selected concept.

TABLE 13

COOLING AND MOISTURE REMOVAL CONCEPT EVALUATION MATRIX

	Cooling and Moisture Removal Concept	Relative Rating					Total, Weighted Rating (B-1/TFA)
		Performance ①	Weight ② (B-1/TFA)	Reliability ③	Maintainability ④	Cost	
I	Direct cooling with precooler, direct flow sorbent bed, ground cooling fan	Unacceptable	Unacceptable	8.15	7.15	-	Unacceptable
II	Direct cooling with precooler, regenerable sorbent bed, ground cooling fan	8.25	0/0	7.1	7.1	9.55	23.88/23.88
III	Simple vapor cycle, electric-drive, ground cooling fan	7.0	9.2/9.4	7.0	7.0	8.5	31.[illegible]/31.3
IV	Simple vapor cycle, pneumatic-drive, ground cooling fan	7.0	9.8/9.8	5.5	5.5	8.7	29.72/29.72
V	Compound three-wheel vapor/air cycle	9.0	10.0/10.0	5.55	5.55	8.6	31.93/31.93
VI	Simple air cycle with precooler, direct flow sorbent bed	9.0	8.4/9.0	9.5	8.0	9.5	35.2/35.8
VII	Simple air cycle with precooler, regenerable sorbent bed	7.6	6.3/4.0	7.7	7.2	8.7	31.24/28.94
VIII	Simple air cycle with precooler, regenerator with recirculation loop	9.3	6.6/7.0	10.0	10.0	10.0	35.9/36.3
IX	Three-wheel bootstrap air cycle with precooler	9.5	8.3/7.4	8.85	8.35	8.2	34.72/33.82
X	Two-wheel bootstrap air cycle, regenerator with recirculation loop, ground cooling fan	9.95	2.8/2.1	7.2	7.2	9.0	30.03/30.33
XI	Three-wheel bootstrap air cycle with precooler and regenerator with recirculation loop	10.0	1.0/1.0	9.0	8.2		28.52/28.52

① Based on 7.0 for meeting 80 gr/lb and less than 200°F, with up to 1.0 for lowered moisture level, and up to 2.0 for lowered drive power requirement.
② Based on linear plot of weight vs rating, assigning 1.0 to heaviest excluding concepts 1 and 2 based on fixed weight only
③ Based on 5.0 assigned to controls, etc, for all cycles.
④ Scaled by reliability, with 1.0 less for sorbent bed changing and 0.5 for water separator coalescer bag changes.

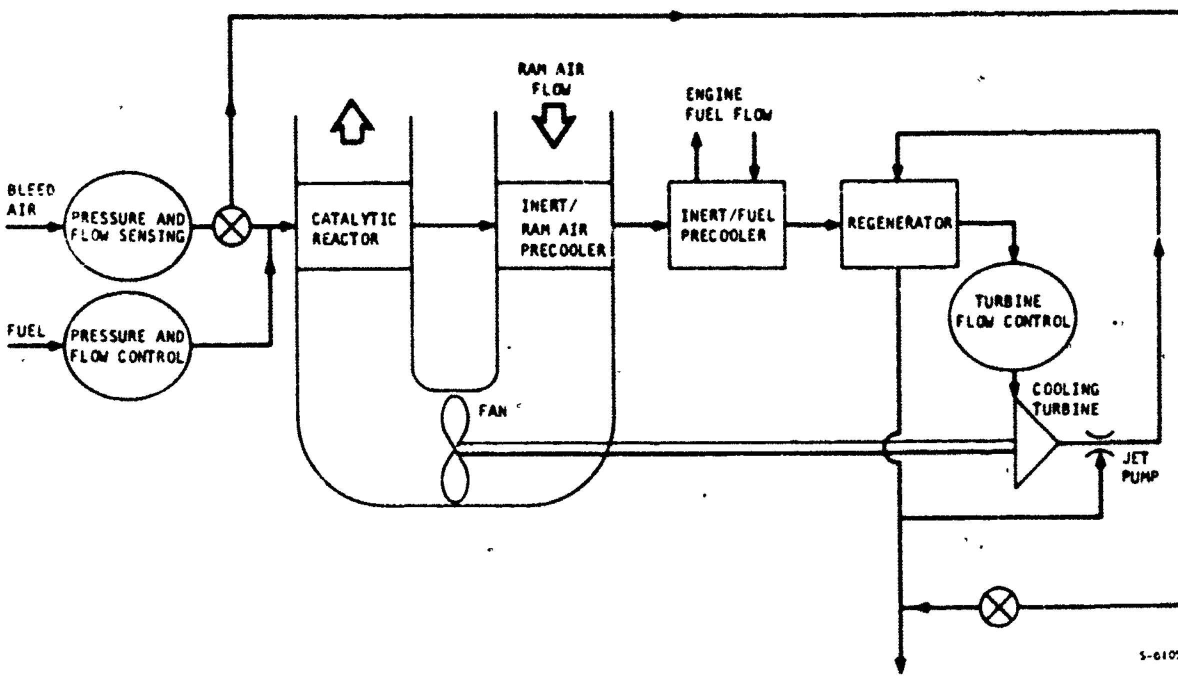


Figure 47. Selected Inert Gas Generator Simplified Schematic

Effect of Changes in Inerting System Requirements

The selected concept retains its weight advantage over a broad range inflow quantities since most of the system weight is independent of the inflow quantity. And changes in the flow will not affect the rating of this concept relative to the others for reliability, maintainability, cost, or volume. Also, minor alterations in the relative emphasis given the various selection criteria will not alter the concept selection since Concept VIII has a rating several percent higher than the next highest concept (Concept VI). Additionally, it should be noted that the weight of Concept VIII is potentially reducible rather considerably if aluminum, instead of stainless, heat exchangers are feasible. The weight of Concept VI will not be changed much by this possibility.

SECTION III

BASELINE LIQUID NITROGEN INERTING SYSTEM PRELIMINARY DESIGN

INTRODUCTION

This section summarizes the performance capabilities of a liquid nitrogen inerting system designed for the B-1 aircraft. The liquid nitrogen system design can be used as a baseline for comparison with the inert gas generator system. Liquid nitrogen inerting systems have undergone flight testing on a variety of aircraft and are sufficiently developed to be applied to production aircraft without further development.

QUANTITY OF NITROGEN REQUIRED FOR INERTING

Most of a liquid nitrogen inerting system weight is the liquid nitrogen itself. Thus, a reasonably careful analysis of the total quantity of nitrogen required is essential. This is in contrast to the inert gas generator system in which almost all of the system weight is attributable to the flow capability desired of the components.

Tank Pressurization Gas

The data presented in Appendix A show that about 525 lb of inert gas are required for tank pressurization on a representative B-1 mission.

Scrubbing Flow

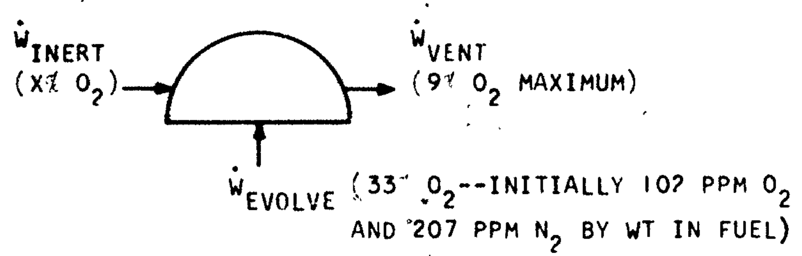
As the aircraft climbs to altitude during a flight, the oxygen saturated in the fuel at sea level pressure starts to evolve as the ambient pressure is reduced. Thus, it is necessary to provide a flow of inert gas to the fuel tanks during this initial climb if the tank ullage space is to be maintained below 9 percent oxygen by volume. Figure 48 shows a mathematical model of the flow balance required during oxygen evolution. Assuming that the oxygen equilibrium saturation pressure is proportional to the tank pressure, it is possible to determine the rate at which inert flow must be input to the fuel tanks. This is shown in Figure 49 for an inert inflow of pure nitrogen. Integrating over the climb to 65,000 ft, the data indicate that about 78 lb of nitrogen are required per 100,000 lb of fuel carried.

In comparison, an inert gas generator inerting system must provide a scrubbing inflow 2.25 times that required with pure nitrogen, assuming that the IGG system outputs a gas containing 5 percent oxygen by volume.

Reserve Gas Supply

A reserve margin of 20 percent has been assumed.

MODEL



EQUATIONS

$$\left.\begin{array}{l}\dot{W}_{INERT} + \dot{W}_{EVOLVE} = \dot{W}_{VENT} \\ X\dot{W}_{INERT} + 0.33\ \dot{W}_{EVOLVE} \leq 0.09\ \dot{W}_{VENT}\end{array}\right\}\ \dot{W}_{INERT} = \frac{0.24\ \dot{W}_{EVOLVE}}{(0.09-X)}$$

$$W_{EVOLVE} = \frac{309 \times 10^{-6}}{14.7}(14.7-P_{AMB})\ W_{FUEL}$$

$$\dot{W}_{EVOLVE} = -21 \times 10^{-6}\ \dot{P}_{AMB}\ W_{FUEL}$$

$$\dot{W}_{INERT} = \frac{-5.05\ \dot{P}_{AMB}}{(0.09-X)}(W_{FUEL} \times 10^{-6}$$

Figure 48. Determination of Inflow Required for Fuel Scrubbing

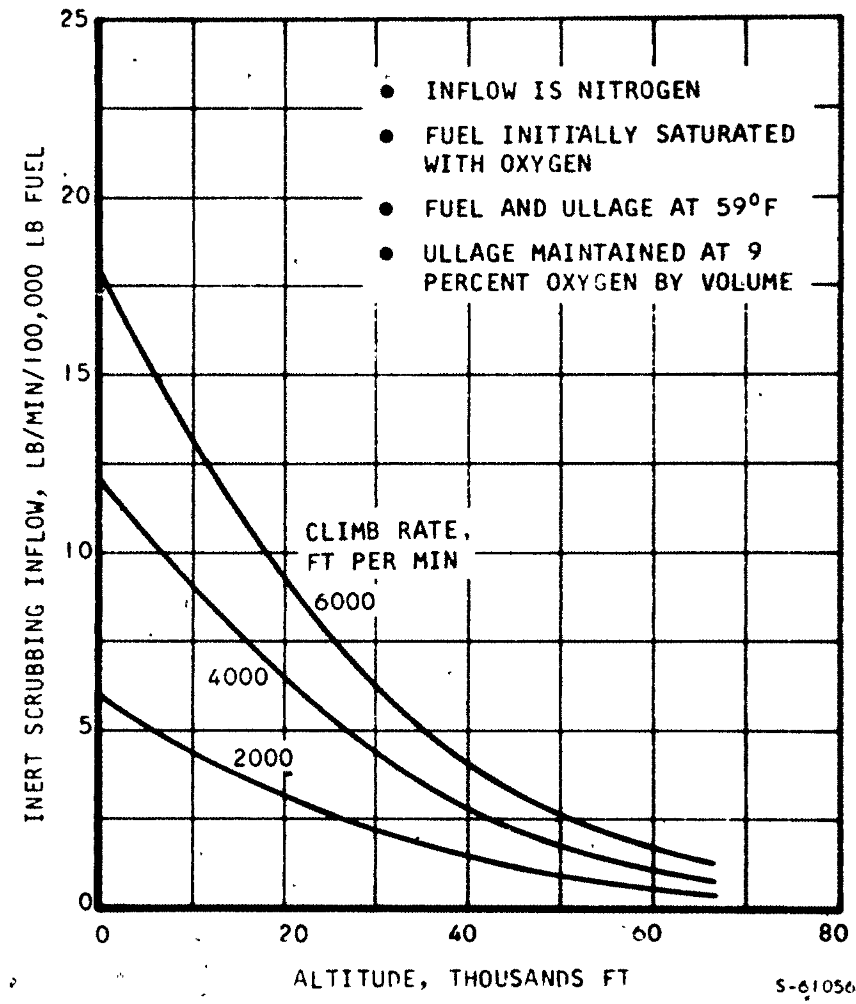


Figure 49. Inert Scrubbing Inflow vs Aircraft Altitude

Total Gas Quantity

Table 14 totals the gas requirements, indicating that almost 900 lb of nitrogen is required for the baseline system for the B-1. A considerable weight savings can be obtained, however, if the following operating techniques are employed:

- Load the fuel into the tanks through spray manifolds that expose all of the fuel to the inert gas in the tank. Test data by WPAFB indicate that this reduces the scrubbing gas requirement by about 85 percent

- Provide the tank pressurization gas by mixing the nitrogen with an available air source, such as engine bleed air. This would reduce the pressurization gas quantity by about 43 percent if the nitrogen flow was diluted to 9 percent oxygen by volume

Table 14 shows the resultant quantity of nitrogen required with these variations in the system operation.

TABLE 14

NITROGEN QUANTITIES REQUIRED FOR B-1

Item	Baseline Quantity	Variant Quantity
Tank Pressurization	525 lb (100% nitrogen)	300 lb (mixed with 225 lb bleed air)
Fuel Scrubbing	200 lb (fuel loaded in bulk into tanks)	30 lb (fuel loaded by spraying into tanks)
Reserve (20%)	145 lb	66 lb
Total Required	870 lb	396 lb
Nominal Design Value	900 lb	400 lb

SYSTEM CONFIGURATION

Figure 50 shows a schematic of the recommended liquid nitrogen inerting system configuration. Figure 51 shows the details of the storage tank component flow arrangement. The system is configured in such a manner that multiple tanks can be used if dictated by the available aircraft packaging envelope. Also, the concept can accommodate mixing of the nitrogen with bleed or ambient air using either a jet pump or throttling valve so that the nitrogen quantity required for tank pressurization is reduced. Liquid is withdrawn from the cryogenic storage tank and is vaporized in a bleed-air heat source warm-up heat exchanger. The ambient temperature vapor is then distributed to the fuel tank upon demand. Although it is possible to design systems in which the liquid nitrogen is input directly to the fuel tanks, it is recommended that a gaseous distribution system be used. Such a system maintains all the distribution lines at ambient temperature so that there is no safety hazard to

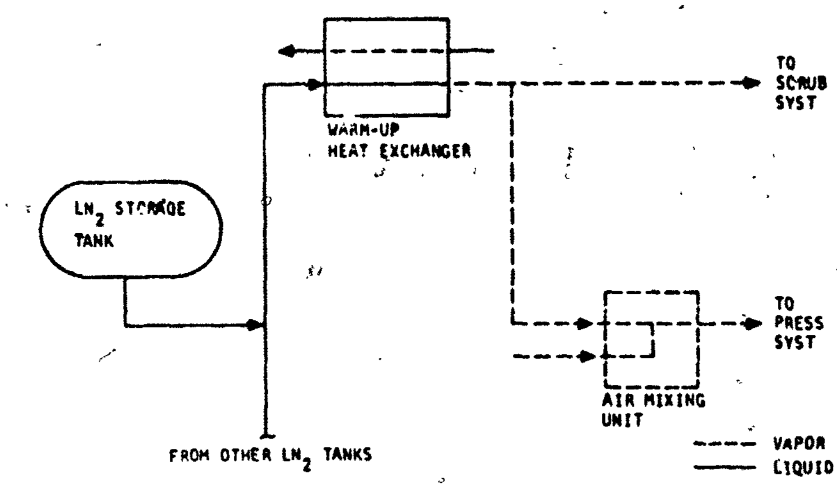
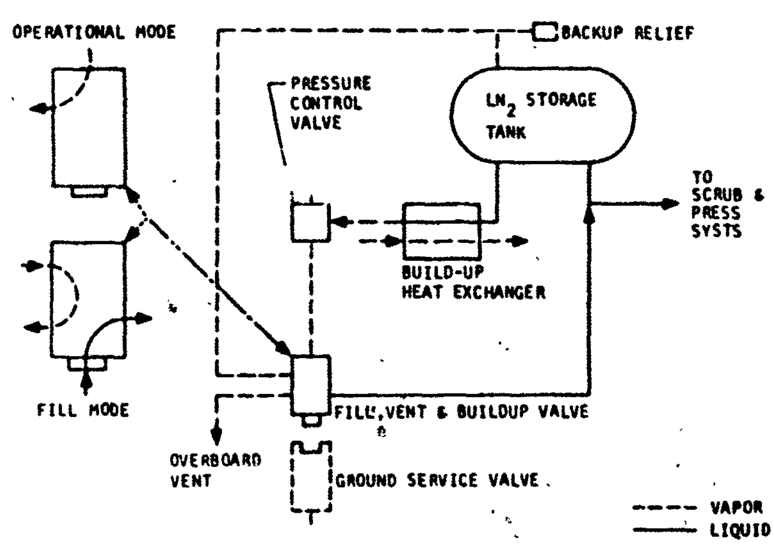


Figure 50. Liquid Nitrogen Inerting System Schematic



STORAGE TANK COMPONENTS

Figure 51. Liquid Nitrogen Inerting System Storage Tank Components

aircraft maintenance personnel. Such a concept also eliminates the possibility of flooding a fuel tank with liquid nitrogen in the event of a control valve malfunction. It should be noted that using gaseous distribution with a liquid nitrogen inerting system facilitates later conversion to an inert gas generator system since only the gas source must be changed.

Cryogenic Tank Design

The cryogenic tank weight is dependent upon the total quantity of nitrogen to be stored and upon the time between tank filling and fluid use. This standby time will size the tank insulation thickness. Nitrogen can accept rather large heat inputs at liquid temperatures, however, without an excessive fluid expansion or pressure buildup. Therefore, to minimize the tank weight, it is necessary to delay tank pressurization to the operating pressure until fluid delivery is required.

Because of the long standby period, heat leak into the cryogenic tank is critical. There is a tradeoff between heat leak (implying insulation weight and quantity of gas vented during standby. Figure 52 shows the weight of a tank designed for 30 days standby as a function of the tank insulation thickness. The data indicate that the tank weight will be less than 10 percent of the total quantity of fluid to be delivered to the fuel tanks. This assumes a tank insulated in the manner used for space vehicle vacuum jacketed tanks. Such technology is state-of-the-art and has demonstrated performance potential.

The tank data presented in Figure 52 also assume that the tank maximum operating pressure is 80 psia. At this pressure, the inner shell thickness is somewhat above the minimum allowable gage thickness for this size tank, but the pressure was selected for the following reasons:

- It provides an optimum insulation thickness of one in --higher pressures would lower this optimum, but test data on low heat leak tanks using multiple radiation-shield insulation indicate that there is noticeable insulation conductivity increase for thicknesses much below one in.
- It makes the nitrogen temperature at delivery pressure slightly above that required for liquefaction of oxygen, thereby eliminating a potential safety problem
- It provides a large pressure head for operating a bleed air/nitrogen jet pump to augment the nitrogen flow if desired

Weight

The total liquid nitrogen inerting system weight is tabulated in Table 15 for systems delivering 900 and 400 lb. These weights exclude the distribution lines to the fuel tanks and the valving on the fuel tanks. Either system can be packaged within a cube circumscribed about the spherical cryogenic tank (excepting distribution lines and tank valving). For the 900-lb system, the tank diameter is about 3.5 ft. For the 400-lb system, it is about 2.7 ft.

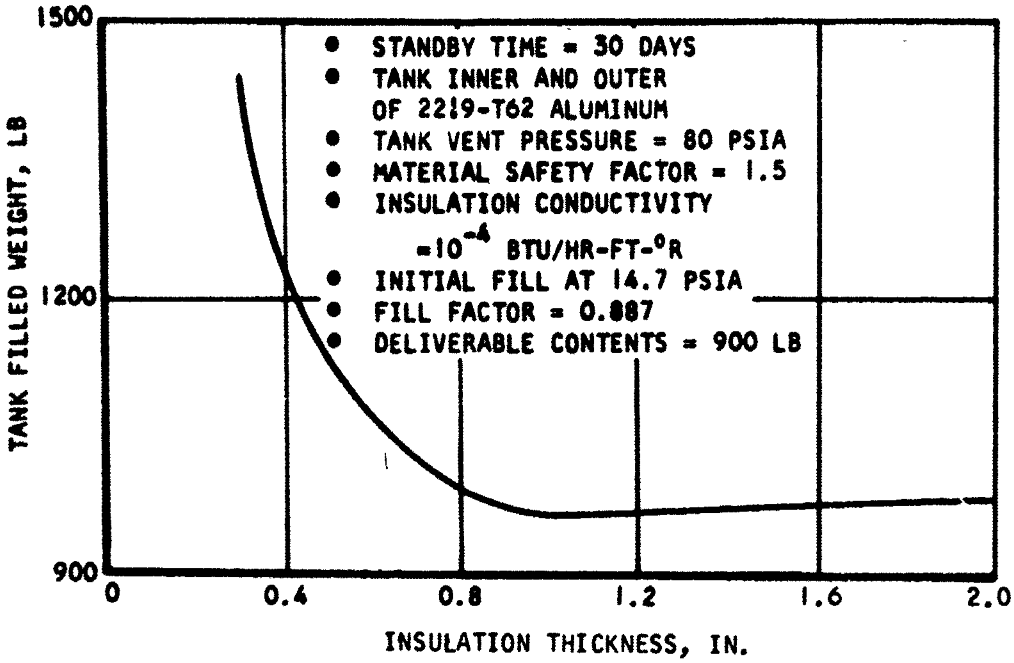


Figure 52. Nitrogen Tank Weight vs Insulation Thickness

TABLE 15

LIQUID NITROGEN INERTING SYSTEM WEIGHT

Item	Baseline Design (900 lb deliverable)	Variant Design (400 lb deliverable)
Deliverable Nitrogen	900	400
Tank and Ullage	66	42
Bui'dup Heat Exchanger	20	20
Plumbing and Valving	10	12
TOTAL	996 lb	474 lb

S-61061

SECTION IV

INERT GAS GENERATOR INERTING SYSTEM PRELIMINARY DESIGN

INTRODUCTION

This section presents the preliminary design of the inert gas generator inerting system selected by the studies presented in Section II. Objectives of the preliminary design phase are:

- Establish inerting system performance over the envelope of aircraft flight operations
- Determine system weight and component specifications
- Establish control concepts and techniques
- Determine packaging configuration

Figure 53 shows the sequence of steps used to perform the preliminary design process.

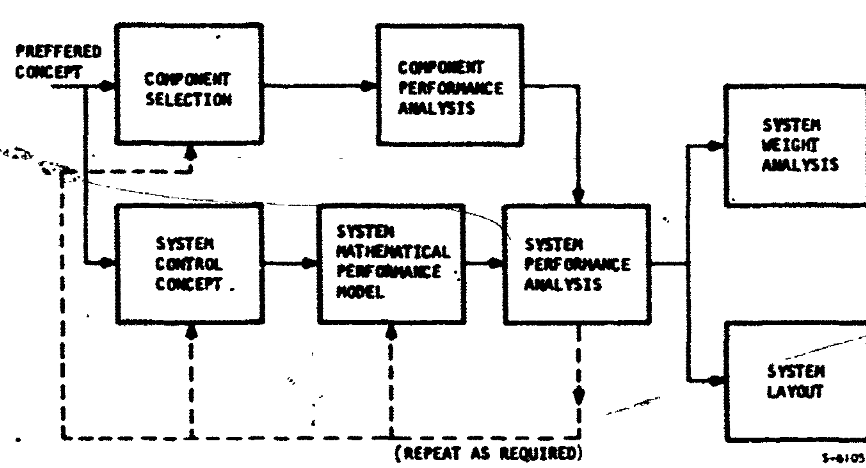


Figure 53. Preliminary Design Logic Diagram

Organization

The material in this section is arranged as follows:

- System Description--system schematic, weight, packaged configuration
- System Operation and Control Techniques--discussion of control concepts required to ensure adequate system performance under all operating conditions
- System Performance Summary--data showing output gas composition as a function of aircraft operating conditions
- Component Performance Data--details of the performance requirements for each major system component

SYSTEM SCHEMATIC DESCRIPTION

Figure 54 shows a detailed schematic of the selected inert gas generator fuel tank inerting system. This system was selected as the best candidate concept based on the data presented in Section II.

The system uses a ram air cooled catalytic reactor to provide an inert gas source. An inert/ram air precooler and an inert/fuel precooler are used to cool the reactor output to temperatures approximating room temperature. Then, the gas is further cooled in the regenerator whose heat sink is the cooling turbine discharge flow. Finally, the inert passes through the cooling turbine and the regenerator before being discharged to the fuel tanks.

A dual nozzle turbine is used to provide relatively high turbine efficiency over a large range of throughflows. To enhance the cooling capability of the regenerator, and to eliminate freezing at the turbine discharge line, a portion of the regenerator discharge flow is mixed with the turbine discharge in a jet pump located on the turbine.

Flow Capability

As shown in Figure 54, the emergency descent flow of up to 200 lb/min is obtained by bypassing flows in excess of 67 lb/min around the catalytic reactor and air cycle refrigeration unit, via the ACM bypass valve. This allows almost all of the system to be sized for a flow of 67 lb/min. The nominal inert oxygen content is 2.5 percent (allowing a control band of ±2.5 percent) so that during the emergency descent flow mode, the oxygen content would climb to about 7.5 percent nominal.

It is recommended that the system be maintained in operation continuously throughout flight. This facilitates rapid response to sudden changes in fuel tank pressure. Consequently, there is a strong incentive to minimize the minimum system flow rate. A minimum flow capability of 6 lb/min was selected based on a tradeoff of increased turbine complexity to obtain lower flows vs the increased moisture content resulting from degradation in low-flow turbine performance.

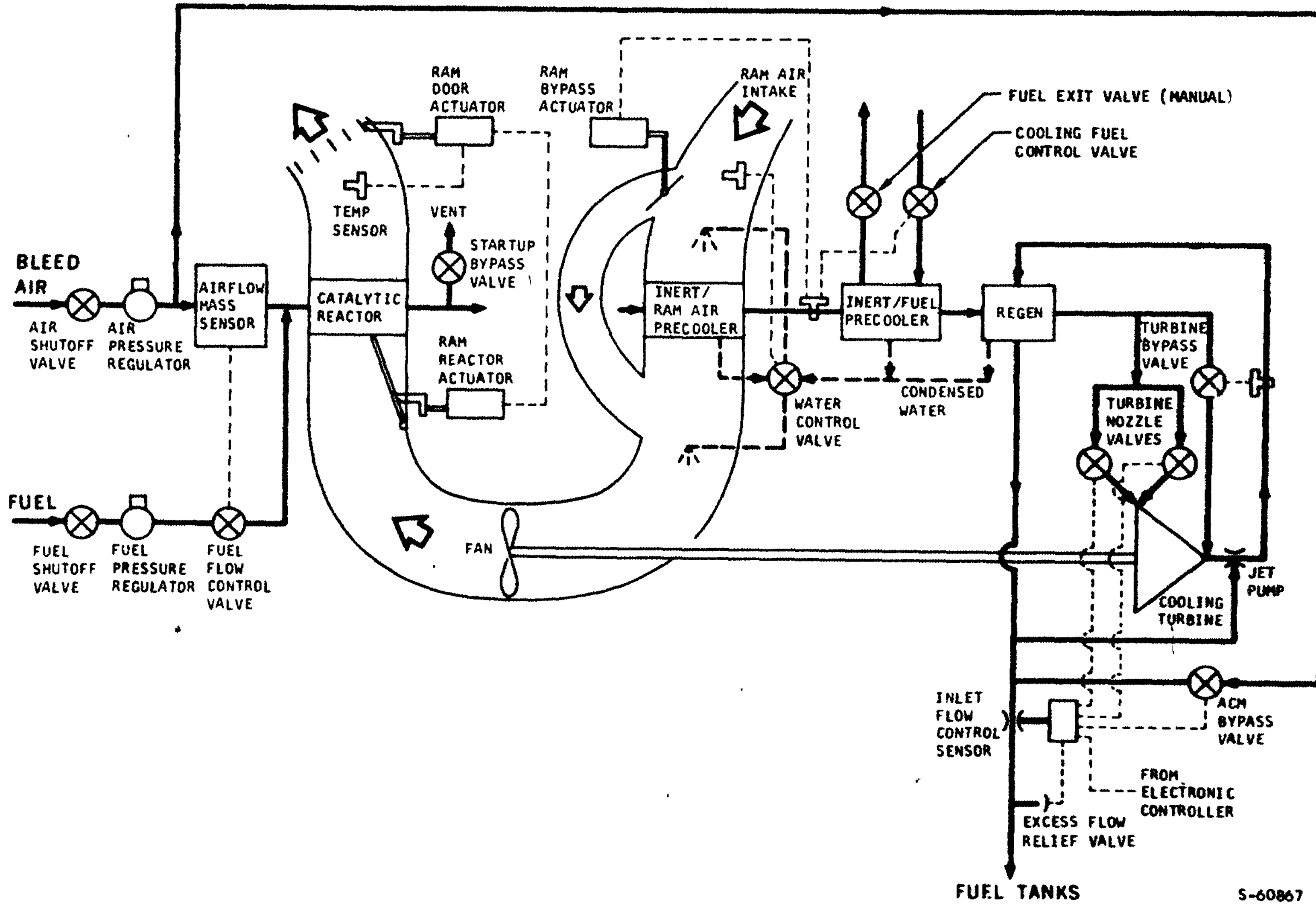


Figure 54. Inert Gas Generator System Detailed Schematic

Weight

The weight of the system components is tabulated in Table 16. The weight estimate excludes the weight of the distribution lines and valving used to route the inert flow from the inert gas generator to the aircraft fuel tanks. An additional weight item that should be considered is the weight of the fuel consumed by the catalytic reactor. Also, the drag penalties associated with ram air usage and the engine power penalty for bleed air could be included in the table. Analyses indicate that the total equivalent fuel penalty to generate inert gas (including fuel, ram air, and bleed air usage) is about 8 lb fuel/100 lb of inert gas. The weight estimate assumes that all heat exchangers are of stainless steel; however, it appears probable that the regenerator can be made of aluminum, thus reducing its weight by about 50 percent.

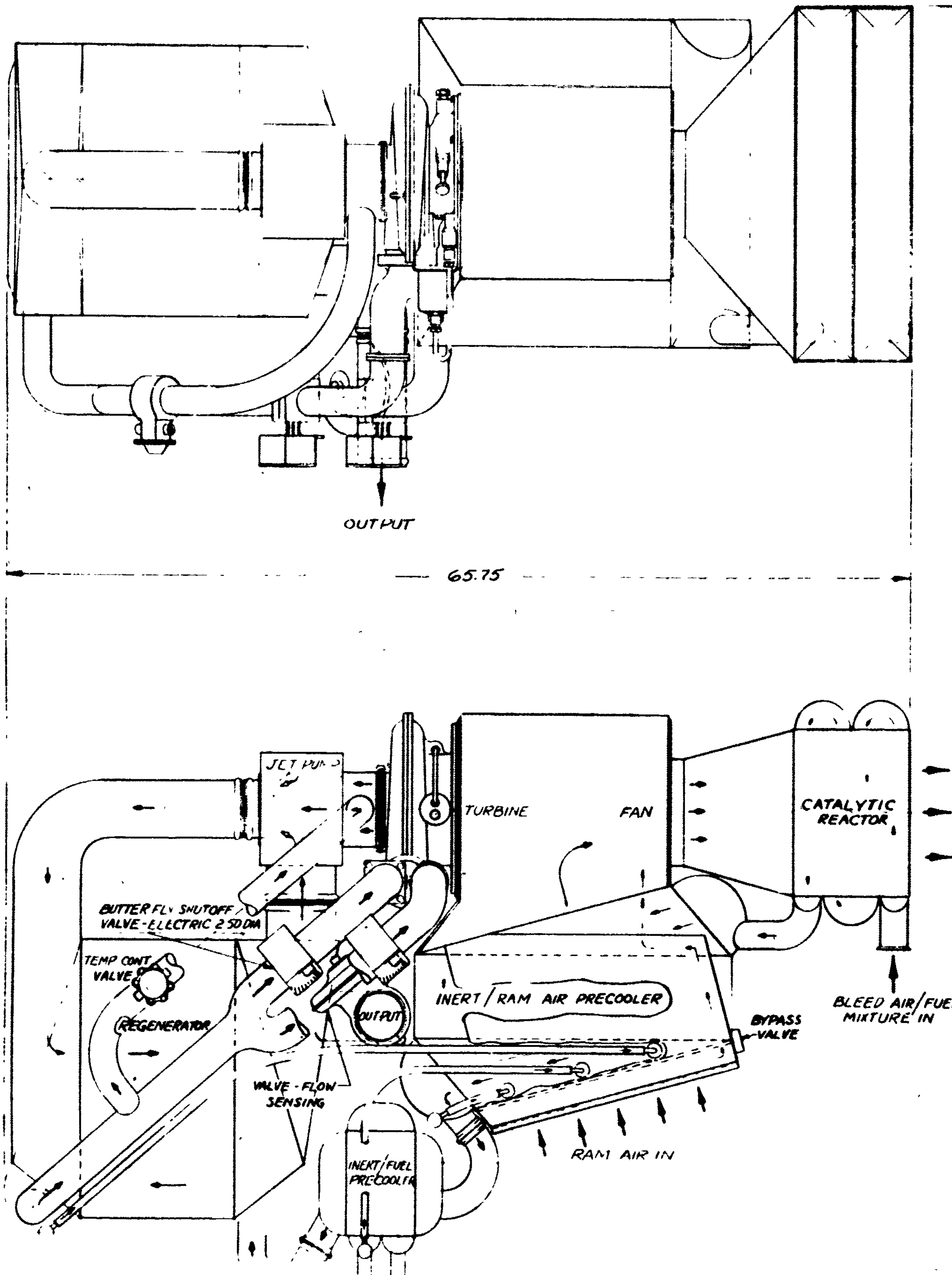
Packaging

Figure 55 shows a packaged configuration of the inerting system. The overall size of the unit is about 5.5 by 3.5 by 2.5 ft. Most of the components, however, are relatively small so that the system packaging arrangement can be easily altered to suit the available envelope onboard the aircraft. In particular, it might be desirable to locate the catalytic reactor in an engine nacelle and to locate the other system components in a less stringent environment. Such a concept would place the reactor in portion of the plane that is already designed to accommodate the high temperature of the ram air discharged from the reactor.

TABLE 16

INERT GAS GENERATOR SYSTEM WEIGHT

ITEM	WEIGHT, LB	ITEM	WEIGHT, LB
CATALYTIC REACTOR	88.0	AIR PRESSURE REGULATOR	5.0
PRIMARY HEAT EXCHANGER	212.0	AIR FLOW MASS SENSOR	1.5
INERT/FUEL HEAT EXCHANGER	17.0	STARTUP BYPASS VALVE	3.0
REGENERATOR	259.0	WATER CONTROL VALVE	0.5
AIR CYCLE MACHINE	28.0	TURBINE NOZZLE VALVES	3.0
EJECTOR	1.5	TURBINE BYPASS VALVE	3.0
RAM DOOR ACTUATOR	5.0	ACM BYPASS VALVE	5.0
RAM BYPASS ACTUATOR	2.0	EXCESS FLOW RELIEF VALVE	1.5
RAM REACTOR ACTUATOR	2.0	INERT FLOW CONTROL SENSOR	2.0
FUEL SHUTOFF VALVE	1.0	ELECTRONIC CONTROLLER	3.0
FUEL PRESSURE REGULATOR	1.5	INERT GAS DUCTING	10.0
FUEL FLOW CONTROL VALVE	3.0	RAM AIR DUCT	4.0
COOLING FUEL CONTROL VALVE	2.0	FIRE PROTECTION INSULATION	5.0
FUEL EXIT VALVE	1.0	MISCELLANEOUS	25.0
AIR SHUTOFF VALVE	5.5	GRAND TOTAL	700.0 LB


OUTPUT
65.75
JET PUMP
TURBINE
FAN
CATALYTIC REACTOR
BUTTERFLY SHUTOFF VALVE-ELECTRIC 2.50 DIA
TEMP CONT VALVE
REGENERATOR
OUTPUT
INERT/RAM AIR PRECOOLER
BYPASS VALVE
BLEED AIR/FUEL MIXTURE IN
VALVE-FLOW SENSING
INERT/FUEL PRECOOLER
RAM AIR IN

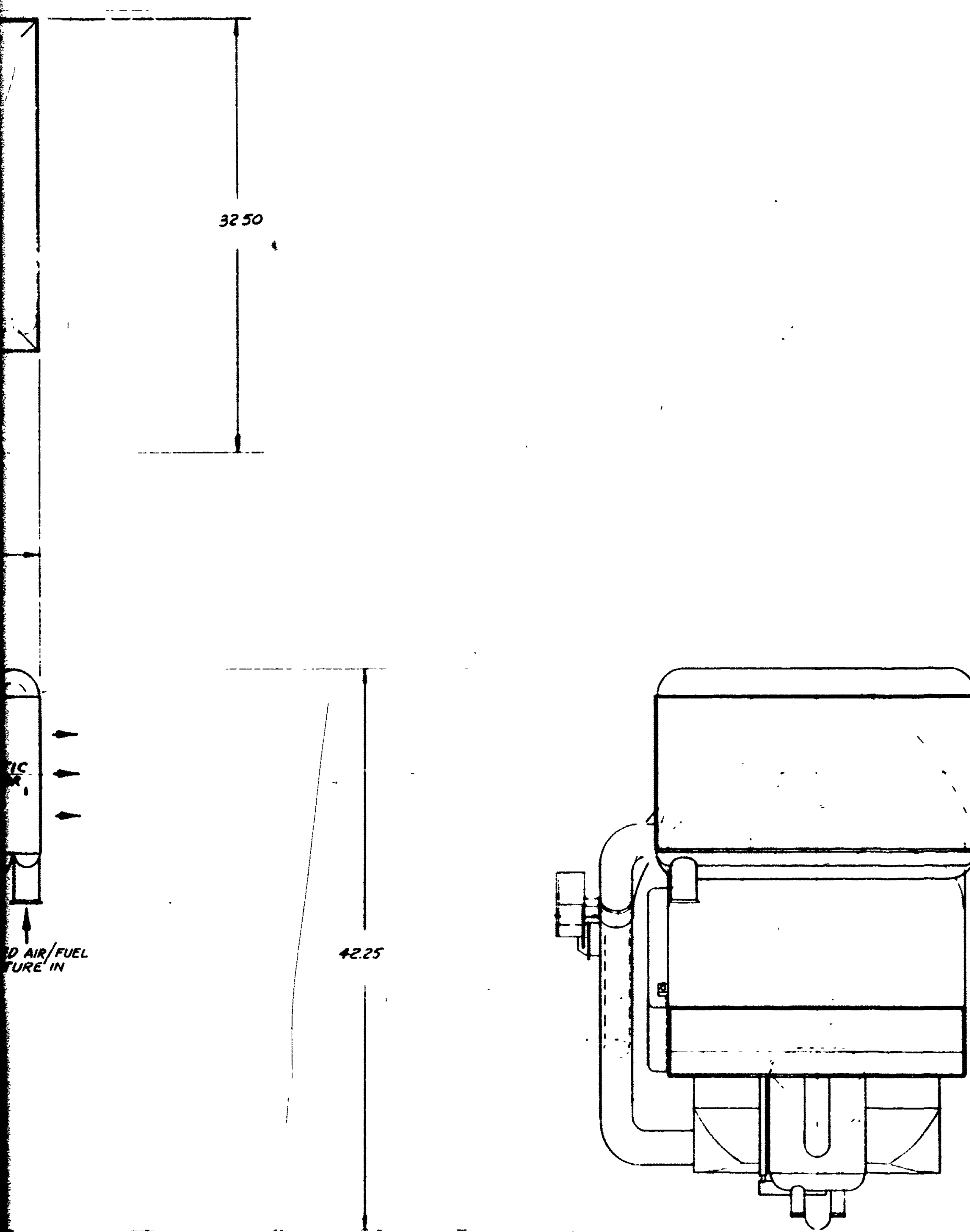


Figure 55. Inert Gas Generator Packaging Configuration (AiResearch Drawing SK60110)

2

SYSTEM OPERATION AND CONTROL TECHNIQUES

The recommended operational and control techniques have been evolved by the iterative process shown in Figure 53. Initially, it appeared that a complex electronic controller would be the optimum method of fulfilling the various control functions. The system performance studies, however, have shown that it is possible to accomplish many of the control functions by sensing temperatures at appropriate locations within the system.

Primary Operational Requirements

The primary inerting system operational requirements are tabulated in Table 17. These requirements formed the basis for the selected system control techniques.

Primary Control Concepts

Table 18 shows the primary control concepts necessary to fulfill the requirements of Table 17. These concepts have been established by a trial-and-error process in which a candidate control technique was implemented in the system performance program and the effects of the control technique were then indicated for all aircraft operating modes. The hardware for implementing these control techniques is shown on the detailed system schematic, Figure 54, and is included in the system weight summary.

Additional Control Requirements

Of lesser importance, but still necessary for satisfactory system operation, are the additional control requirements shown in Table 19. These requirements are flow limiting during operation with battle damage, inflow control to accomplish fuel scrubbing, and display and control of system faults. They can be implemented either pneumatically or electrically by accomplishing the analog functions shown in Figure 56.

Startup/Shutdown Sequencing

In addition to the control functions shown in Figure 56, the inerting system controller must provide the correct sequencing of valving to accomplish startup and shutdown. Table 20 shows the sequencing actions that must occur.

SYSTEM PERFORMANCE SUMMARY

The performance calculations presented in Section II were performed by hand and were adequate to allow selection of the optimum inerting system concept; however, to more accurately predict system performance and to establish performance over a large range of operating conditions (over 100 different aircraft operating conditions have been considered), a computer program was generated. This program was based on the programming techniques and subroutines developed at AiResearch to support the design of aircraft environmental control systems.

TABLE 17

PRIMARY INERTING SYSTEM OPERATIONAL REQUIREMENTS

REQUIREMENTS	METHOD OF ACCOMPLISHMENT	REASONS/BENEFITS
PROVIDE PROPER MASS INFLOW TO FUEL TANKS	• FLOW CONTROL VALVE ON AIR CYCLE PACK DISCHARGE LINE USING TANK ΔP SENSOR TO CONTROL VALVE POSITION	• MAINTAINS FUEL TANK PRESSURE AT SLIGHT POSITIVE PRESSURE DIFFERENTIAL RELATIVE TO AMBIENCE • LOCATION ON PACK DISCHARGE MINIMIZES SENSITIVITY TO SUDDEN BLEED PRESSURE CHANGES (OCCURRING ON THROTTLE CHANGE)
PROVIDE PROPER INERT GAS OXYGEN COMPOSITION	• CONTROL FUEL/AIR RATIO AT REACTOR INLET BY MEASURING AIR MASS FLOW AND SCHEDULING FUEL VALVE POSITION	• ESSENTIAL IF TANK ATMOSPHERE IS TO BE INERT • OFFERS BETTER CONTROL THAN SENSING OUTPUT OXYGEN CONTENT
PROVIDE PROPER INERT GAS MOISTURE COMPOSITION	• USE AIR CYCLE REFRIGERATION PACK WITH RAM AIR AND FUEL COOLING TO CONDENSE MOISTURE	• AIR CYCLE REFRIGERATION SHOWS DECIDED WEIGHT AND PERFORMANCE ADVANTAGES OVER VAPOR CYCLE REFRIGERATION OR SORBENT BED MOISTURE REMOVAL CONCEPTS

TABLE 18

PRIMARY INERTING SYSTEM CONTROL REQUIREMENTS

REQUIREMENTS	METHOD OF ACCOMPLISHMENT	REASONS/BENEFITS
CONTROL CATALYTIC REACTOR RAM FLOW OUTLET TEMPERATURE	• MODULATE RAM AIR DUCT OPENING USING RAM OUTLET TEMPERATURE SIGNAL TO DRIVE ACTUATOR TO MAINTAIN RAM DISCHARGE AT 1000°F	• MAINTAINS REACTOR HOT ENOUGH TO SUSTAIN REACTION AT ALL TIMES • PREVENTS REACTOR OVERHEATING BY ASSURING ADEQUATE COOLING FLOW • MINIMIZES RAM FLOW AND HENCE MINIMIZES DRAG PENALTIES ASSOCIATED WITH SYSTEM
CONTROL PRIMARY HEAT EXCHANGER RAM AIR FLOW	• BYPASS PORTION OF RAM FLOW AROUND PRIMARY USING INERT DISCHARGE TEMPERATURE SIGNAL TO DRIVE BYPASS VALVE TO MAINTAIN INERT DISCHARGE AT 100°F	• PREVENTS FREEZING WATER OUT OF INERT DURING SUBSONIC CRUISE AT ALTITUDE
CONTROL WATER SPRAYED INTO RAM FLOW UPSTREAM OF PRIMARY HEAT EXCHANGER	• USE RAM INLET TEMPERATURE TO PRIMARY TO SWITCH WATER SPRAY TO DOWNSTREAM OF PRIMARY WHEN RAM TEMPERATURE IS BELOW 80°F	• PREVENTS COOLING RAM FLOW TO A POINT AT WHICH FREEZING COULD OCCUR IN RAM SIDE OF PRIMARY HEAT EXCHANGER
CONTROL FUEL FLOW TO INERT/FUEL HEAT EXCHANGER	• USE INERT DISCHARGE TEMPERATURE FROM PRIMARY HEAT EXCHANGER TO TURN ON COOLING FUEL FLOW WHEN TEMPERATURE EXCEEDS 120°F	• ALLOWS MOISTURE REMOVAL TO BE ACCOMPLISHED DURING HIGH SPEED SUPERSONIC CRUISE WHEN RAM TEMPERATURES ARE QUITE HIGH
CONTROL REGENERATOR COLD SIDE INLET TEMPERATURE	• SENSE MIXED FLOW DOWNSTREAM OF EJECTOR AND BYPASS PORTION OF FLOW AROUND TURBINE	• MAINTAINS REGENERATOR COLD SIDE ABOVE 35°F SO THAT FREEZING WILL NOT OCCUR

TABLE 19

ADDITIONAL INERTING SYSTEM CONTROL REQUIREMENTS

REQUIREMENTS	METHOD OF ACCOMPLISHMENT	REASONS/BENEFITS
LIMIT MAXIMUM INFLOW WHEN NOT IN EMERGENCY DESCENT	• SENSE AMBIENT PRESSURE AND RATE OF PRESSURE CHANGE COMPARED WITH AIRCRAFT NORMAL DESCENT CAPABILITY, USE TO OVERRIDE INERT FLOW CONTROL SENSOR	• PREVENTS EXTENDED OPERATION AT 200 LB/MIN FLOW • AVOIDS HIGH FLOW WITH BATTLE DAMAGE IN TANKS
PROVIDE SCRUBBING FLOW DURING INITIAL AIRCRAFT CLIMB	• SENSE AMBIENT PRESSURE AND RATE OF PRESSURE CHANGE, COMPARE REQUIRED FLOW WITH THAT FOR SCRUBBING, USE TO OVERRIDE INERT FLOW CONTROL SENSOR	• MAINTAINS TANK ATMOSPHERE AT LESS THAN 9 PERCENT OXYGEN DURING CLIMB WHEN OXYGEN EVOLVES FROM FUEL
DISPLAY AND CONTROL SYSTEM FAULTS	• SENSE FUEL TANK DIFFERENTIAL PRESSURE • SENSE REGENERATOR COLD PASS DISCHARGE TEMPERATURE • SENSE REACTOR INERT DISCHARGE TEMPERATURE	• SIGNALS FACILITATE FAULT ISOLATION • SIGNALS SHUTDOWN SYSTEM BEFORE EXTENSIVE DAMAGE OCCURS

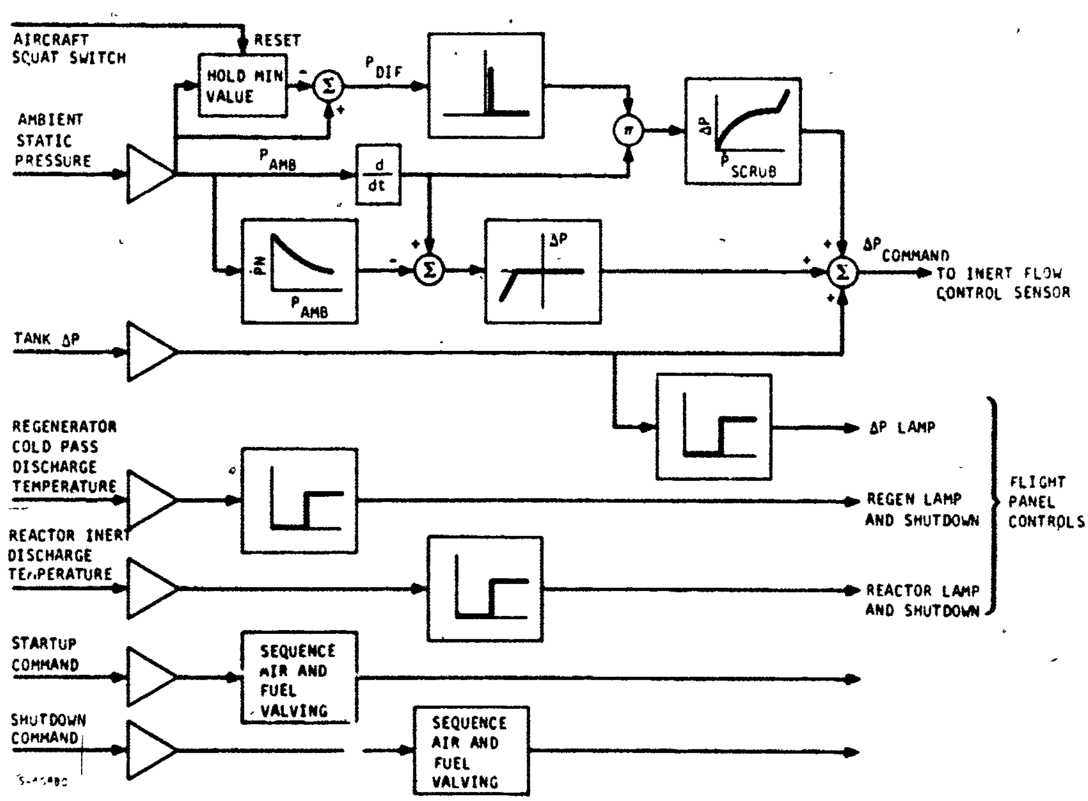


Figure 56. Analog Function for Flow Override and Fault Display/Shutdown

The performance predictions calculated by the program were used as the basis for selecting the recommended system operating procedures. In fact, without the insight provided by the program, many of the control requirements might not have been adequately developed.

Data Input to Program

The program has three different classes of data inputs:

- Working Fluid Properties--data on the specific heat, saturation moisture level, enthalpy, specific heat ratio, etc., were input for air, fuel, and the inert gas constituents (carbon dioxide, argon, nitrogen, oxygen, and water)

- System Component Performance Data--information on the performance parameters of the individual system components (discussed later in this section), allowances for ducting and valving pressure drops, regulator control settings, etc.

- Aircraft Operational Performance Data--aircraft altitude, ambient temperature and moisture, airspeed, fuel temperature, bleed air pressure and temperature, and desired system flow rate

Data Output by Program

Once the selected control system had been established, the inputs for the working fluid properties and the system component performance data were the same for all cases considered. Thus, the only variables for each case became the aircraft operational performance data. For each set of performance data, the program provides the following output information:

- Summary listing of working fluid and system component parameters

- Listing of component performance for catalytic reactor, inert/ram air precooler, inert/fuel precooler, regenerator, cooling turbine, and jet pump

- State points (pressure, temperature, and moisture) and the inlet and outlet of each system component for the inert flow, the ram airflow, and the cooling fuel flow

- Summary of the output inert gas composition, including moisture content

Assumed Engine Bleed Air Data

The bleed air pressures used for the performance calculations are shown in Table 21. Figure 57 shows a comparison of the bleed air pressure available from two different existing high-bypass engines. The data show that the bleed pressures used in the performance calculations are conservative. It should be noted that the air pressure regulator is set at 100 psia so that higher bleed pressures are not actually used in the inerting system.

TABLE 20

INERTING SYSTEM START UP/SHUTDOWN SEQUENCING

ITEM	SEQUENCE	ACTION
STARTUP	1	OPEN STARTUP BYPASS VALVE ALLOWING REACTOR OUTPUT TO FLOW OVERBOARD (LINE SIZED TO ALLOW ABOUT 67 LB/MIN THROUGHFLOW
	2	OPEN AIR SHUTOFF VALVE
	3	MONITOR REACTOR OUTPUT TEMPERATURE, HOLD 15 SEC AFTER IT REACHES 400° F
	4	OPEN FUEL SHUTOFF VALVE
	5	OPEN FUEL FLOW CONTROL VALVE TO 0.67 LB MIN NOMINAL INFLOW OF [illegible] 5 LB/MIN OF AIR
	6	MONITOR REACTOR OUTPUT TEMPERATURE, HOLD FOR 5 SEC AFTER IT REACHES 800° F EXCESS FLOW RELIEF VALVE IS OPEN
	7	CLOSE STARTUP BYPASS VALVE SO FLOW PASSES TO TURBINE AND OUT EXCESS FLOW RELIEF VALVE AND OVERRIDE INERT FLOW CONTROL SENSOR SIGNAL
	8	SWITCH OVER TO OPERATIONAL CONTROL LOGIC AIR FLOW STARTS DECREASING TO 6 LB/MIN, FUEL FLOW DECREASES TO ABOUT 0.36 LB/MIN
SHUTDOWN	1	DRIVE EXCESS FLOW RELIEF VALVE FULL OPEN
	2	CLOSE FUEL SHUTOFF VALVE, AND DRIVE FUEL FLOW CONTROL VALVE TO MINIMUM FLOW POSITION
	3	CLOSE AIR SHUTOFF VALVE

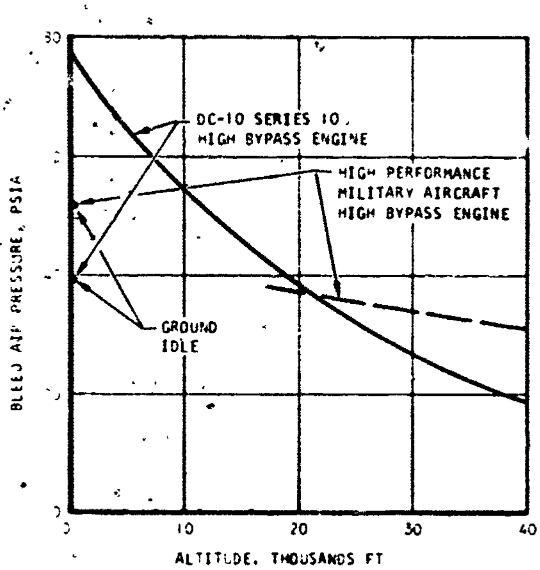


Figure 57. Typical High Bypass Engine Bleed Data

TABLE 21

ENGINE BLEED AIR PRESSURES ASSUMED FOR PERFORMANCE ANALYSIS

MACH NUMBER	ALTITUDE, FT			
	5,000	25,000	40,000	50,000
0.5	100 45**	-	-	-
0.75	100 45**	145	[illegible]	[illegible]
0.90	130	170	155	145
1.5	-	130*	130*	130*
2.0	-	130*	90	[illegible]
GROUND IDLE 35 PSIA				

*REGULATOR SETTING 100 PSIA
**DESCENT CONDITION

Summary of Inerting System Performance

The primary objectives of the performance studies were to establish the correct control concepts and to determine the moisture content that would be present in the inert flow to the fuel tanks. Early in the study, it had been established that the design goals should be a moisture content of less than 80 grains water/lb inert at all times and an integrated mission average of less than 25 grains/lb. These levels are set by the moisture that might be input to aircraft having unpressurized tanks vented to ambience.

To establish moisture content throughout the possible range of aircraft operations, the performance program was used to assess performance at the conditions summarized in Table 22. Approximately 100 different sets of operating conditions are considered. These sets are selected to allow generation of performance graphs applicable to the operating continuum. Since the system performance will improve somewhat as the ambient temperature and humidity are lowered, only the worst-case conditions have been considered. These conditions are based on MIL-STD-210B.

TABLE 22

RANGE OF AIRCRAFT OPERATING CONDITIONS USED FOR PERFORMANCE ANALYSES

Operational Parameter	Ground Operation	Low Altitude Flight	High Altitude Cruise
Inert flow, lb/min	6 to 18	6 to 67	6 to 15
Aircraft altitude, ft	0	5000	25,000 to 60,000
Aircraft speed, Mach No.	0	0.5 to 0.85	0.75 to 2.0
Bleed pressure, psia	35	See Table 21	See Table 21
Ambient temperature, °F	59 to 103	59 to 83.7	*
Ambient humidity, gr/lb	60 to 182	60 to 182	0
Number of cases analyzed	18	57	22

*Ambient temperature depends on altitude, standard day temperatures used.

1. Ground Performance

Figure 58 shows the outlet moisture content of the inert gas as a function of the system flow rate while the aircraft is parked on the ground. The data are applicable to a large range of ambient atmosphere conditions since the system controls minimize the effect of changes in ram air temperature and moisture content.

The peculiar shape of the curve is a result of the interaction between the turbine efficiency and the regenerator effectiveness. At very low flows, the regenerator has a high effectiveness and the turbine pressure is quite low since the nozzles are sized for a considerably larger flow. As the flow is increased, the regenerator effectiveness decreases; (this is a result both of the increased flow and of the change in the performance of the jet pump that provides flow to the cold-side of the regenerator), so that the outlet moisture content increases. Then, as the flow is further increased, the turbine pressure ratio starts increasing so that the refrigeration provided by the inert expanding across the turbine is increased; this enhances the moisture removal capability resulting in a low outlet moisture content.

If the high moisture contents obtained at very low system flows prove excessive, it is possible to design the system in such a manner that the minimum flow rate on the ground is 15 lb/min. At this flow rate, the outlet moisture content is quite low; however, little flow will be input to the fuel tanks while the aircraft is on the ground so that the recommended concept does not include special flow controls for ground operation.

2. Low Altitude Flight Performance

The maximum normal inerting flows will occur during the final phases of descent when the ambient pressure is changing at a high rate. An altitude of 5000 ft was selected as being representative of the point at which the aircraft starts fairing from its descent profile to its landing approach pattern. Figure 59 shows the outlet moisture content vs inert flow rate for various aircraft Mach numbers. Ambient humidity has little effect on the outlet moisture content for a 0.7 Mach number, as shown by Figure 60. Figure 61 shows the outlet moisture content vs aircraft Mach number for various combinations of ambient temperatures and humidities. The data assume that the inerting system input pressure at Mach 0.7 and 0.85 is 100 psia (a cruise condition) and that at Mach 0.5 is 45 psia (a descent case). If the aircraft is assumed to be in descent at Mach 0.7, then the ou' moisture content is increased to values approximating those shown for th 0.5 condition.

3. High Altitude Cruise Performance

At high altitudes, the ambient temperature and humidity show little variation between the cold, standard, and hot days. Therefore, the standard day values have been used to determine the high altitude performance data shown in Figure 62. The data indicate that the outlet moisture content at altitudes above 40,000 ft is nearly independent of the flight speed, being about 4 grains water/lb inert.

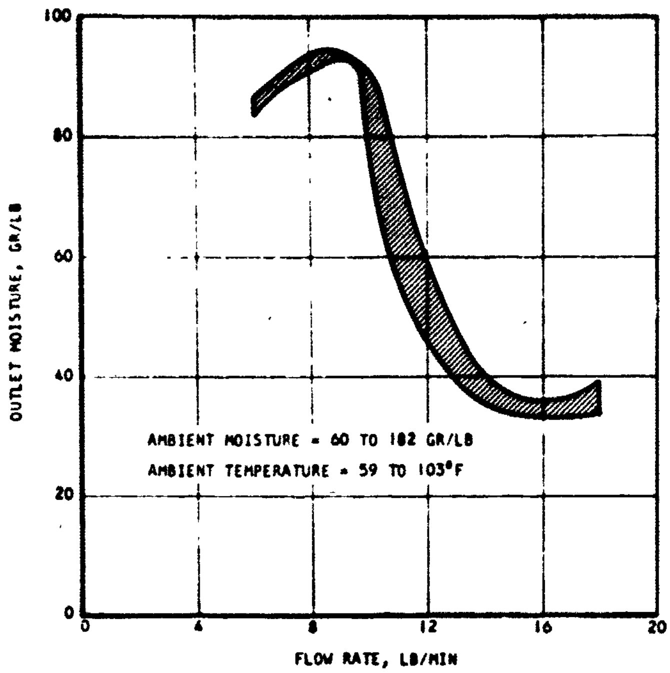


Figure 58. Inerting System Outlet Moisture Content for Ground Operation

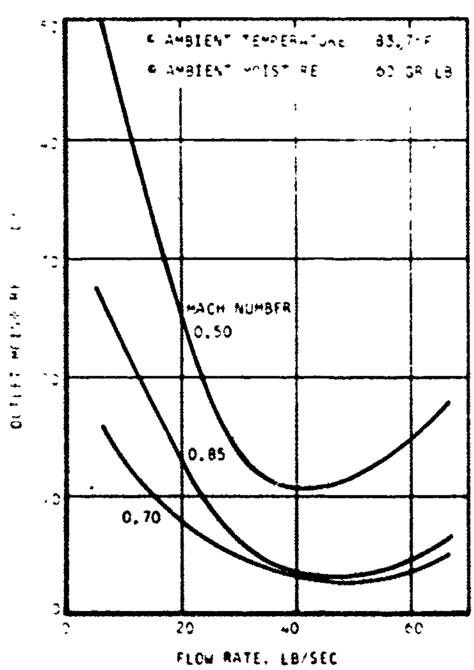


Figure 59. Inerting System Outlet Moisture Content vs Flow Rate at 5000-ft Altitude

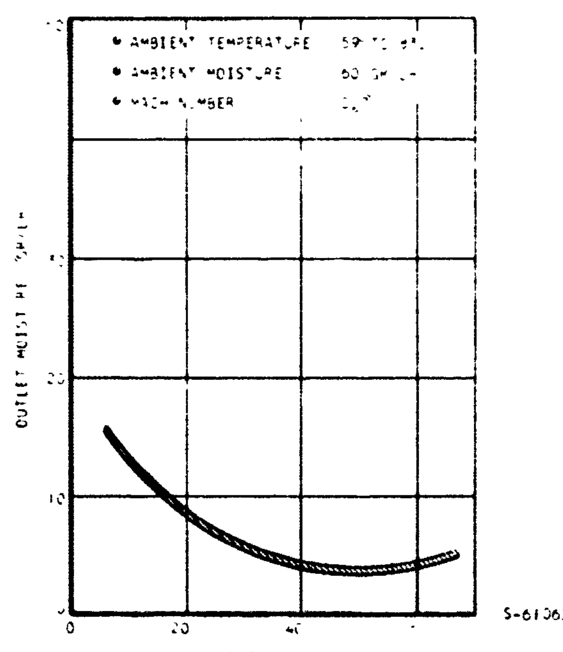


Figure 60. Inerting System Outlet Moisture Content Insensitivity to Ambient Humidity

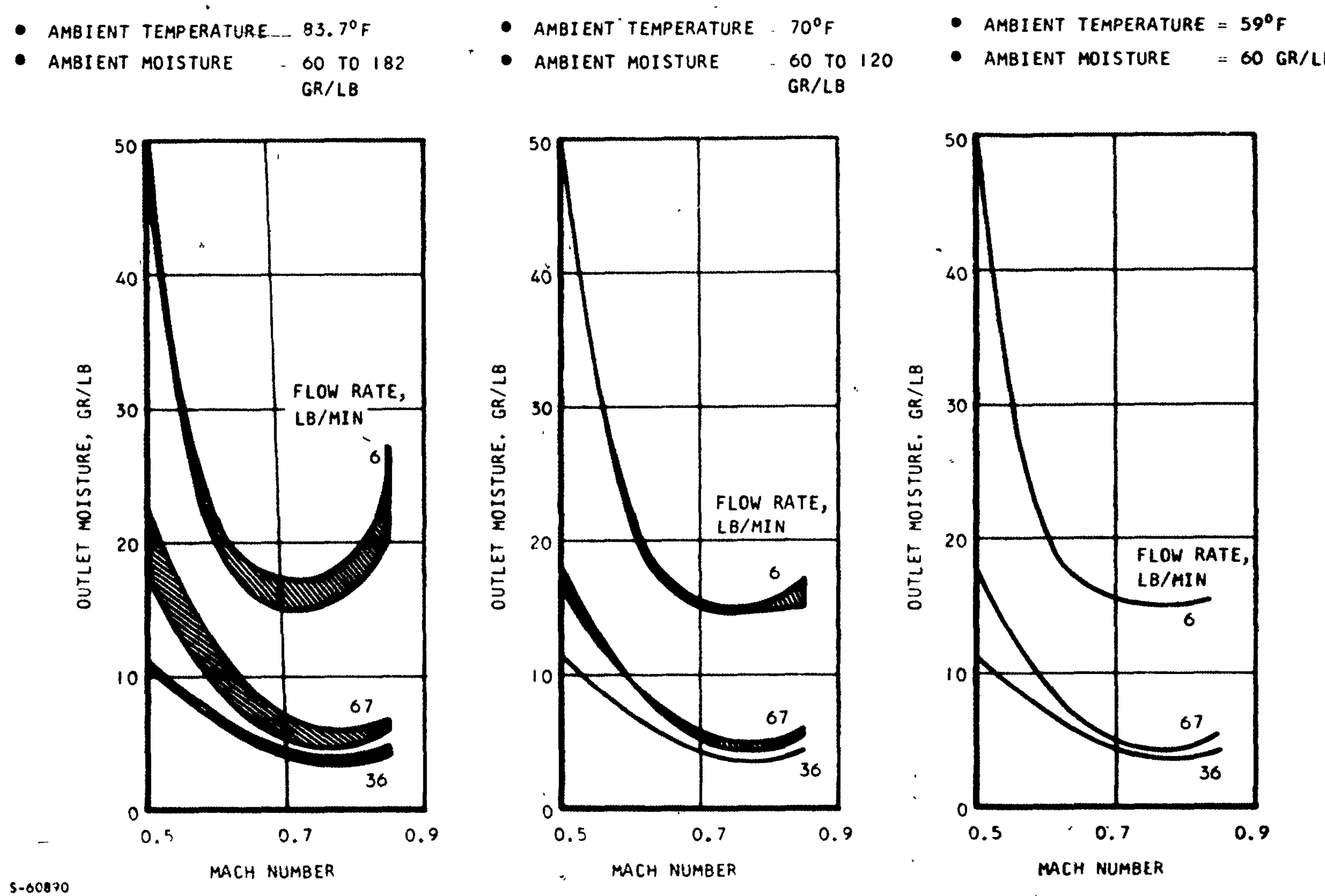


Figure 61. Inerting System Outlet Moisture Content vs Mach Number at 5000 ft Altitude

4. Typical Integrated Mission Performance

Table 23 shows the moisture content in the inert flow for each portion of a typical flight. The data indicate that the average moisture content of the inert gas is about 5.3 grains water/lb inert. The total inert input to the fuel tanks, however, is much less than that generated by the inerting system (which operates over much of the flight at its minimum flow rate), and the inert entering the tanks occurs during those portions of the flight when the moisture content is higher than the average value. Thus, the average moisture content of the inert entering the fuel tanks is 8 to 12 grains water/lb.

5. Typical Inerting System State Points

Table 24 (presented at end of Volume II because of classification shows the state points at each location in the inerting system for four flight conditions:

- Low altitude descent at maximum normal flow
- High altitude cruise at minimum flow
- Low altitude subsonic dash
- High altitude supersonic dash

The aircraft Mach number and altitude for each case are those specified in Appendix A, paragraph 4.8.

COMPONENT PERFORMANCE DATA

Figures 63 through 68 show performance maps for the major system components. These maps were used by the system performance program to predict the outlet temperature, moisture, and pressure. All of the heat exchangers were sized specifically for the inerting system using performance techniques standardly used for aircraft heat exchangers. The turbine performance map is that of an existing aircraft environmental control system turbine. The fan map is a scaled version of an existing aircraft ECS fan.

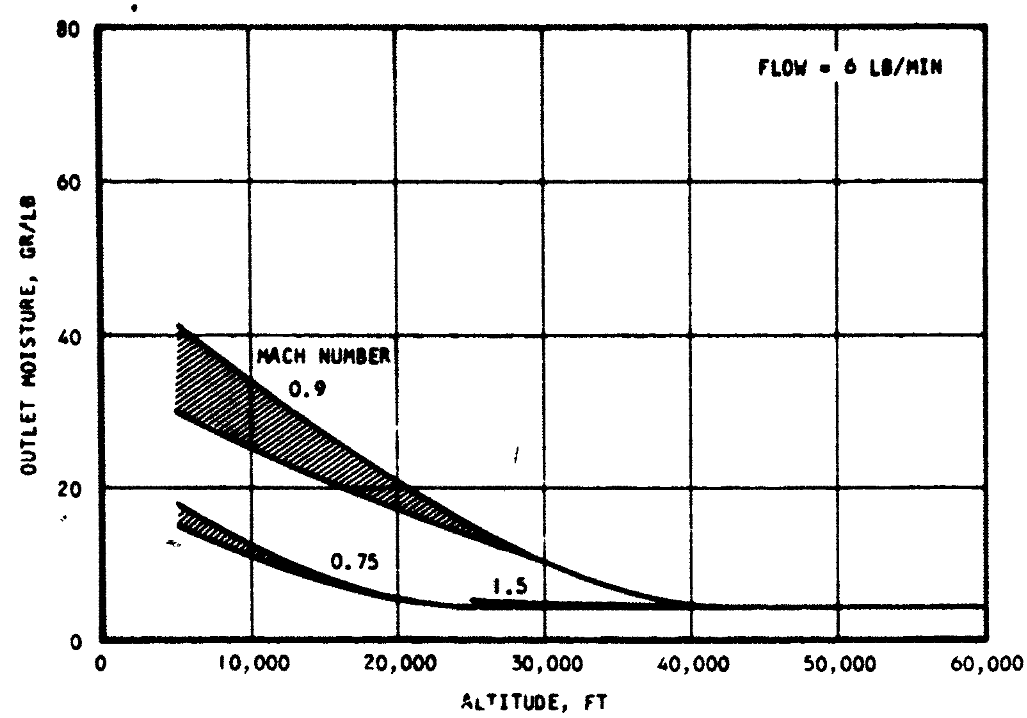


Figure 62. Inerting System Outlet/Moisture Content at High Altitude Flight

TABLE 23

TYPICAL INTEGRATED MISSION MOISTURE CONTENT

ITEM	FLOW RATE LB/MIN	MOISTURE CONTENT, GR/LB	DURATION, HR	INERT INPUT, LB	MOISTURE INPUT, LB
SCRUBBING DURING INITIAL CLIMB	20	8	0.1	120	0.13[illegible]
SUBSONIC CRUISE AT ALTITUDE	6	4	5.0	1800	1.030
LOW ALTITUDE SUBSONIC DASH	6	27	0.5	180	0.695
SUBSONIC CRUISE AT ALTITUDE	6	4	5.0	1800	1.030
CLIMB TO HIGH ALTITUDE	15	4	0.3	270	0.154
HIGH ALTITUDE SUPERSONIC CRUISE	10	4	1.0	600	0.340
DESCENT TO HOLDING PATTERN	10	8	0.2	120	0.137
DESCENT TO LANDING FIELD	10	16	0.2	120	0.274
			12.3 HR	5010 LB	3.797 LB

AVERAGE INFLOW MOISTURE CONTENT = 5.33 GR/LB

S-61062

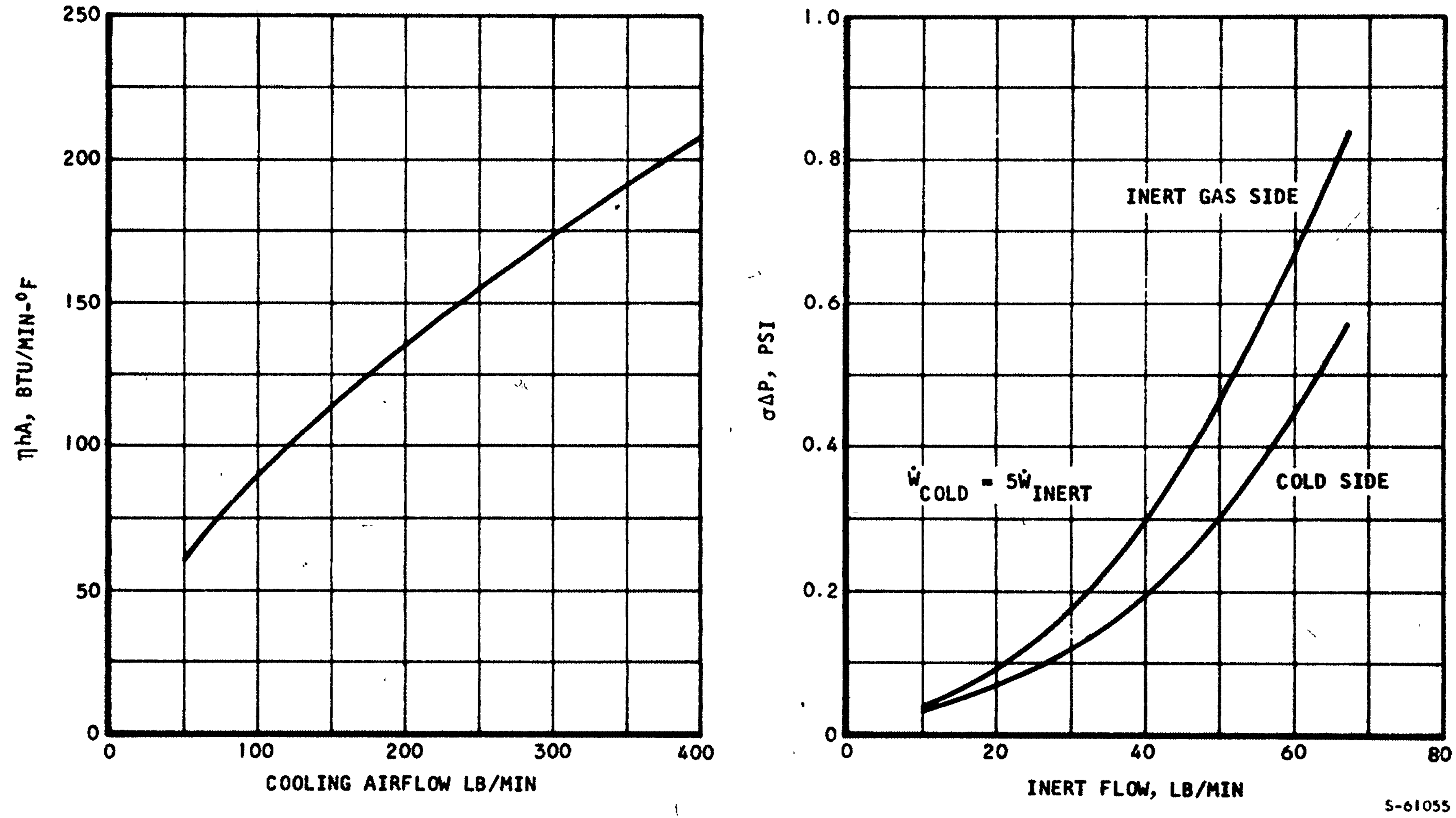


Figure 63. Catalytic Reactor Performance Maps

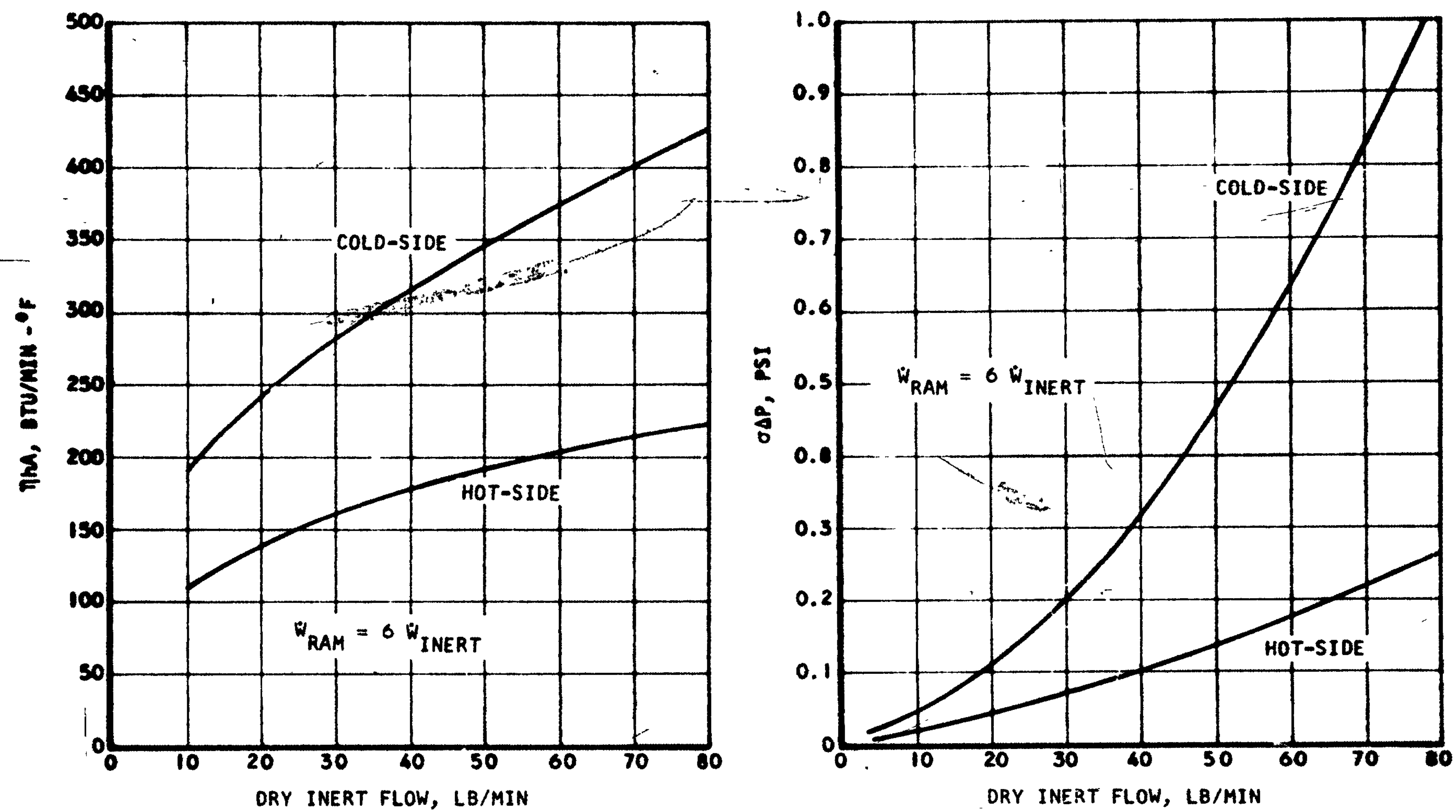


Figure 64. Inert/Ram Air Precooler Performance Maps

S-60889

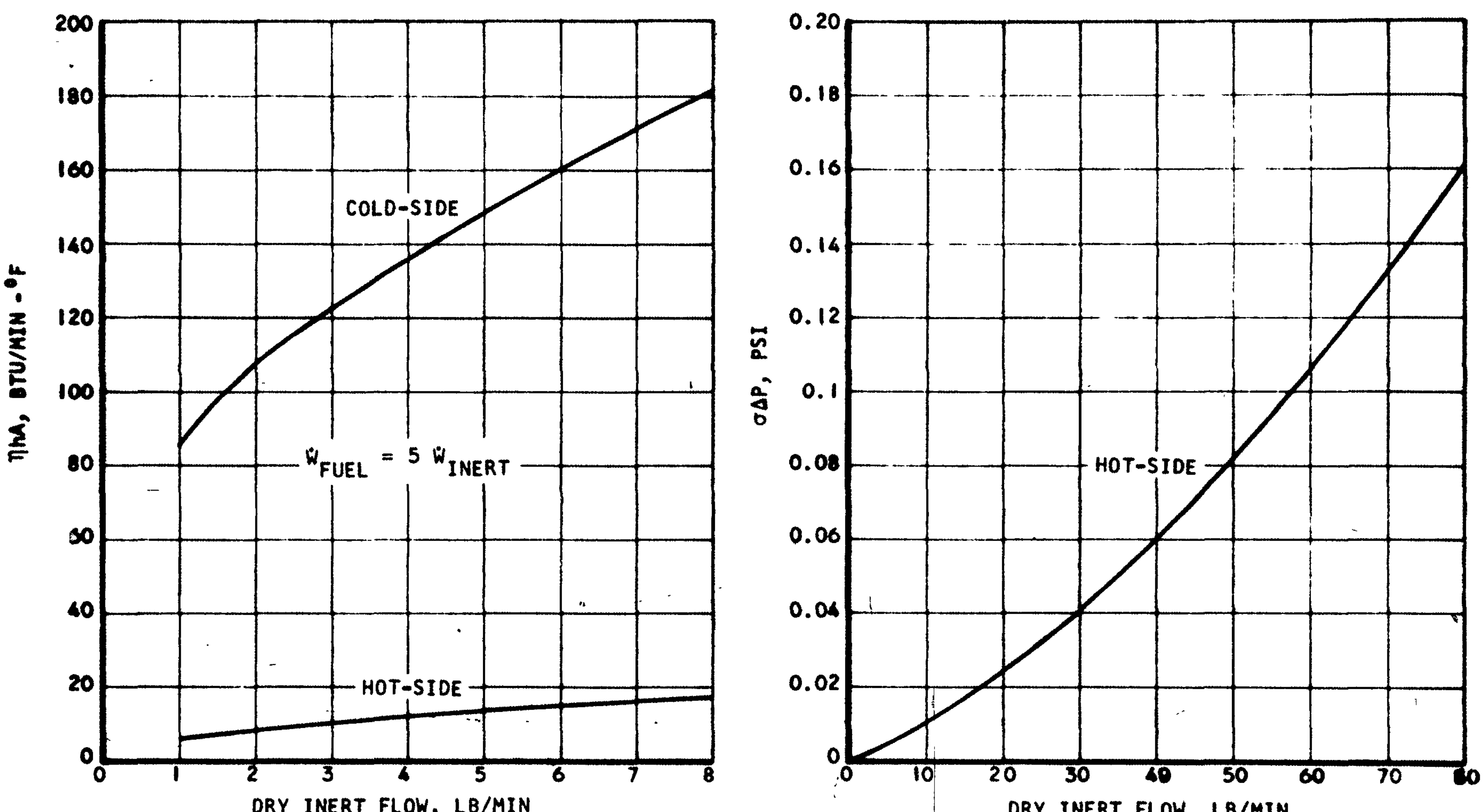


Figure 65. Inert/Fuel Precooler Performance Maps

S-60887

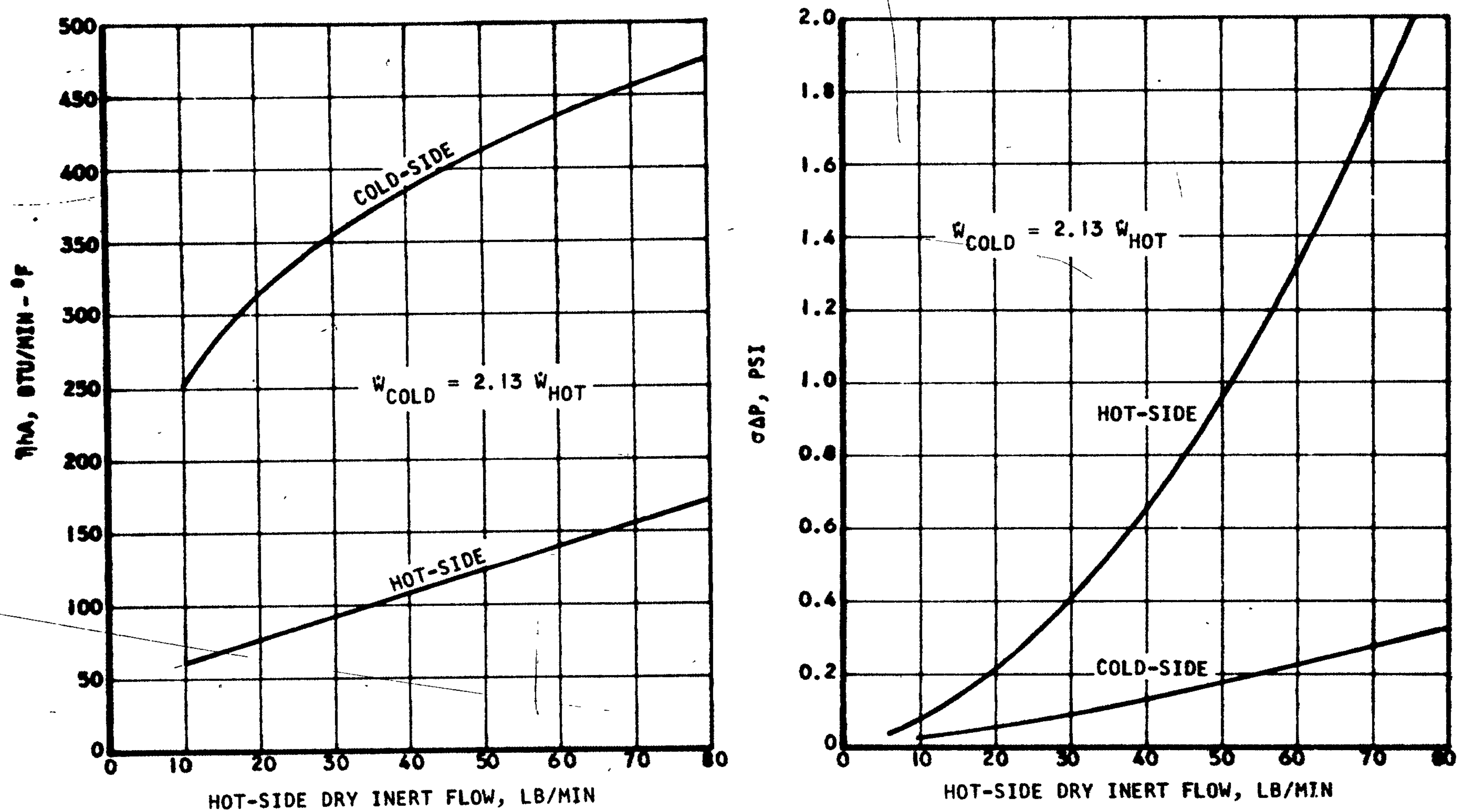
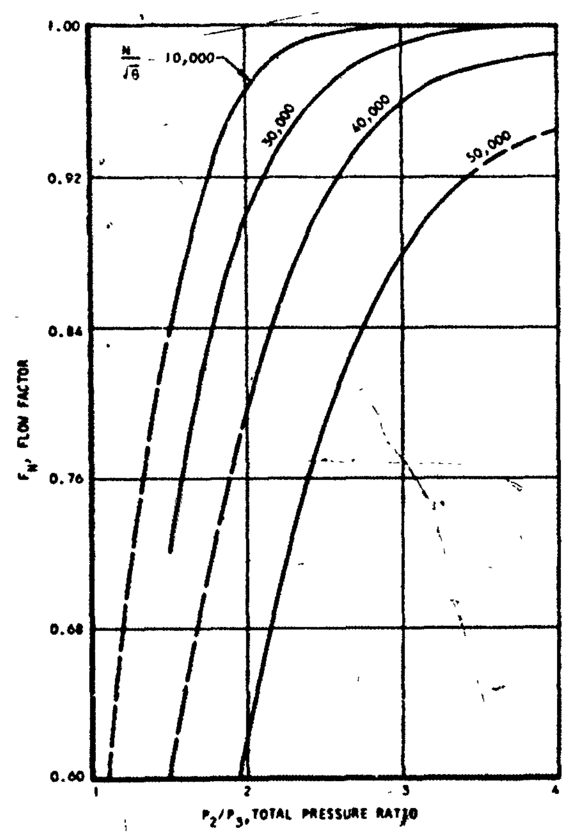
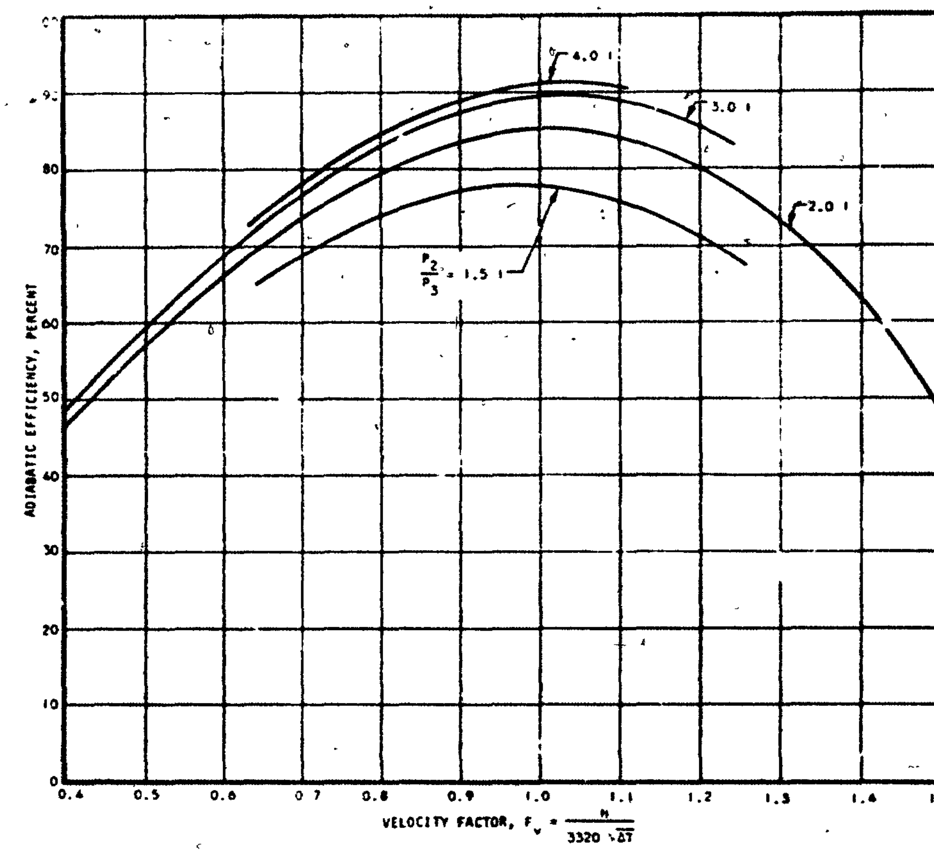


Figure 66. Regenerator Performance Maps

S-60888





N = SPEED, RPM

P_2 = INLET PRESSURE, PSIA

P_3 = TURBINE DISCHARGE PRESSURE, PSIA

T_2 = INLET TOTAL TEMPERATURE, °R

T_3 = DISCHARGE TOTAL TEMPERATURE, °R

W_t = AIRFLOW, LB/MIN

η_t = ADIABATIC EFFICIENCY

A_n = EFFECTIVE NOZZLE AREA = 1.6 SQ IN.

θ = $T_2/519$

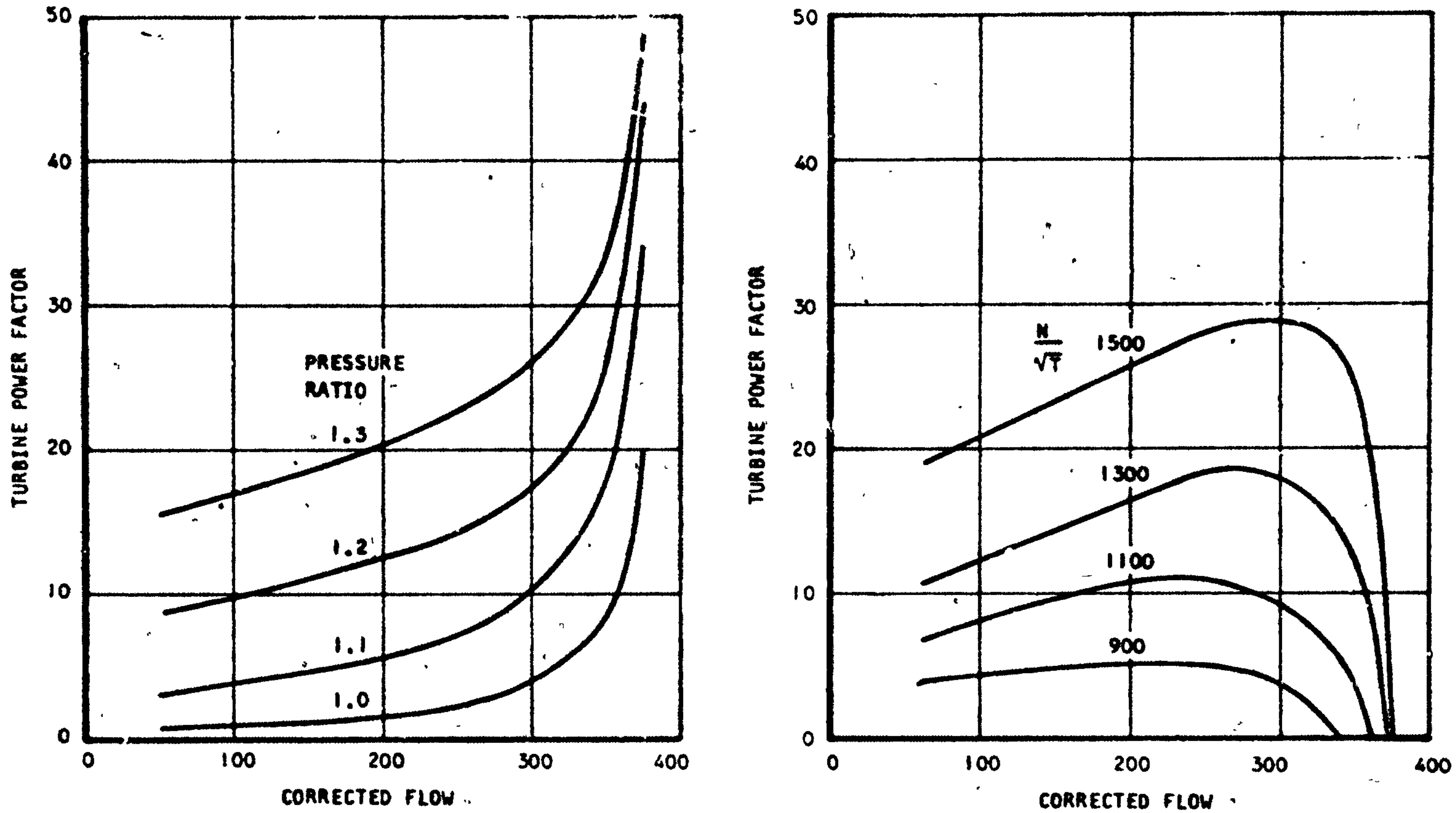
F_N = TURBINE NOZZLE FLOW FACTOR

$$F_N = \frac{W_t\sqrt{T_2}}{(31.82)P_2} \times \frac{1}{A_n}$$

$$\eta_t = \frac{T_2 - T_3}{T_2\left(\frac{Y}{Y+1}\right)} \quad \text{where } Y = \left(\frac{P_2}{P_3}\right)^{0.283} - 1.0$$

S-60866

Figure 67. Turbine Performance Maps



W_F = FAN FLOW, LB/MIN
W_t = TURBINE FLOW, LB/MIN
ΔT_t = TURBINE FLOW TEMPERATURE DROP, °R
P_F = FAN INLET PRESSURE, IN. Hg
T_F = FAN INLET TEMPERATURE, °R
N = ROTATIONAL SPEED, RPM

CORRECTED FLOW $= \dfrac{W_F\sqrt{T_F}}{P_F}$

TURBINE POWER FACTOR $= \dfrac{W_t \Delta T_t}{P_F\sqrt{T_F}}$

S-60872

Figure 68. Fan Performance Maps

PRECEDING PAGE BLANK-NOT FILMED

SECTION V

CATALYST AND CATALYTIC REACTOR TESTING

INTRODUCTION

This section presents the results of the testing performed to select the optimum catalyst for the catalytic reactor and to determine the necessary heat transfer data for reactor design. It summarizes the previous work that has been done and explains the need for the testing performed during this program. The section also documents the test equipment and procedures used to acquire the data.

Objectives

With the exception of the catalytic reactor, the preferred inerting system components are state-of-the-art designs that have been extensively used in aircraft environmental control systems. Therefore, to improve confidence in the overall system concept, it is necessary to accumulate data that would form a basis for design of the catalytic reactor. These data can be classified as follows:

- Catalyst performance data
  - reaction efficiency
  - minimum reaction lightoff temperature
  - inert gas composition (efficiency is an indication of composition)
- Heat transfer design data - heat dissipation along the reactor tubes as a function of
  - inert/cooling airflow ratio
  - inert throughflow
  - inert pressure

Background

A previous study (described in AFAPL-TR-69-68) by American Cyanamid Company has established that catalytic reaction of air and fuel is a feasible method of obtaining inert gas. That study also determined that one catalyst, designated American Cyanamid Code A, shows good potential for an inerting system application. The available data, however, were generated in a diluted atmosphere (oxygen concentrations much less than in air) with a test bed configuration unrepresentative of flight-type heat transfer equipment. Thus, it was necessary to determine catalyst performance in a test configuration closely resembling flight-type heat exchangers, operated with air rather than nitrogen

diluted with oxygen. Additionally, it was important to obtain gas analyses and to measure the exhaust water acidity so that the overall catalyst performance, particularly its conversion efficiency, could be assessed.

The American Cyanamid study revealed two problems with using the Code A catalyst. The first was that the minimum reaction light-off temperature for Code A was between 500 and 600°F (usually near the upper end of this band). This temperature exceeds the temperature at which engine bleed air is available outside the engine nacelle, the bleed temperature is usually limited to about 450°F to reduce fire hazards--and under certain operating conditions bleed temperatures of 200°F are not uncommon). The second problem is that Code A catalyst develops hot spots which randomly traverse the catalyst bed during operation. Both these findings have been confirmed by the testing conducted during this study.

Thus, if the American Cyanamid Code A catalyst is used, it will be necessary to provide some method of obtaining the required lightoff temperature and to provide a means of reducing the hot spots (otherwise excessive cooling airflows that would quench the reaction elsewhere in the bed would be required). Thus, the testing in this study has built upon the starting basis provided by the American Cyanamid study and has been directed towards solutions to these two problems and to obtaining heat transfer data (which was not an objective of the American Cyanamid study).

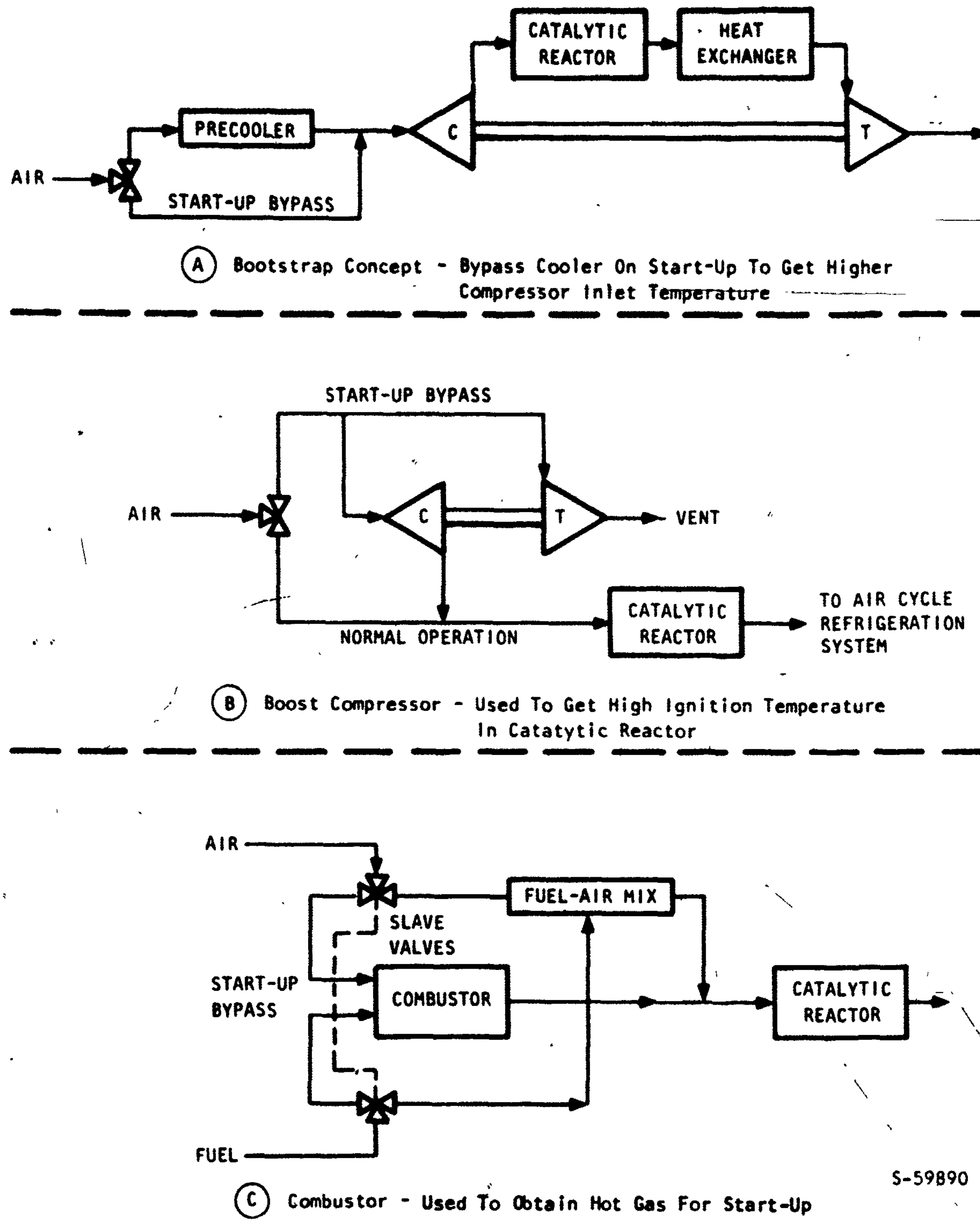
Approach to Solution of Catalyst Problems

In an attempt to eliminate the startup problem with the Code A catalyst, several different methods of raising the bleed temperature at the reactor inlet were investigated. Three such concepts are shown in Figure 69. Figures 70 and 71 show the performance of the concepts of Figures 69A and 69B at the assumed inerting system design point described in Section II. These figures show that one of the concepts (Figure 69A) requires more bleed pressure than is available, and that the other (Figure 69B) requires a large additional bleed airflow. The third concept, a combustor used only during startup, appears to be feasible and is the best of these temperature augmentation concepts. An alternate approach, however, is to evaluate other catalysts in an attempt to obtain a catalyst (or combination of catalysts) having both a lower lightoff temperature and more even reaction distribution within the catalyst bed. It is this approach that has been pursued during this study.

TEST EQUIPMENT

Equipment Description

The test equipment designed for the catalyst and catalytic reactor testing uses a parallel arrangement of 10 tubes (304SS, 0.25 in. OD, 0.010 in. wall, 20 in. long) in which the catalyst is packed. Figure 72 shows a schematic of the tube bundle, indicating the portion of the tubing that is packed with catalyst. Figure 73 is a photograph of the assembled tube bundle. The fuel/air mixture is distributed to the tubes by an inlet manifold and the inert products of reaction are collected from the tubes by an exit manifold.



(A) Bootstrap Concept - Bypass Cooler On Start-Up To Get Higher Compressor Inlet Temperature

(B) Boost Compressor - Used To Get High Ignition Temperature In Catatytic Reactor

(C) Combustor - Used To Obtain Hot Gas For Start-Up

Figure 69. Possible Methods Which May be Employed for Catalyst Light-Off

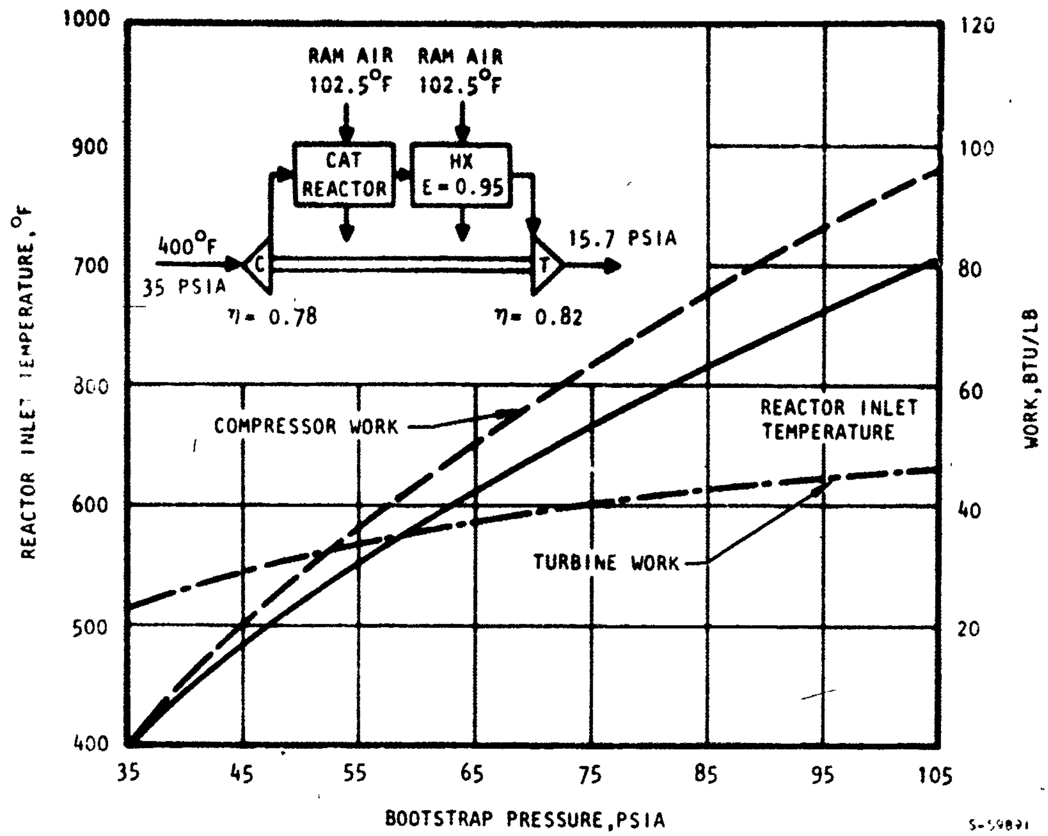


Figure 70. Performance With Catalytic Reactor Within Bootstrap Cycle Aircraft at Mach 0.7, Sea Level, Hot Day)

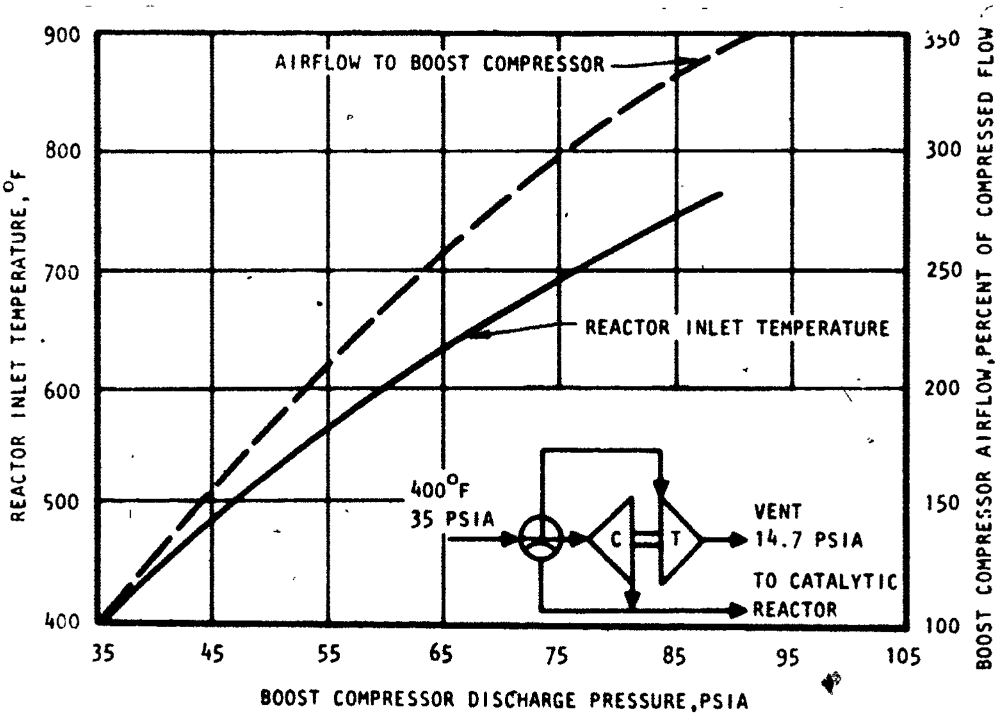


Figure 71. Boost Compressor Airflow Requirements and Reactor Inlet Temperature

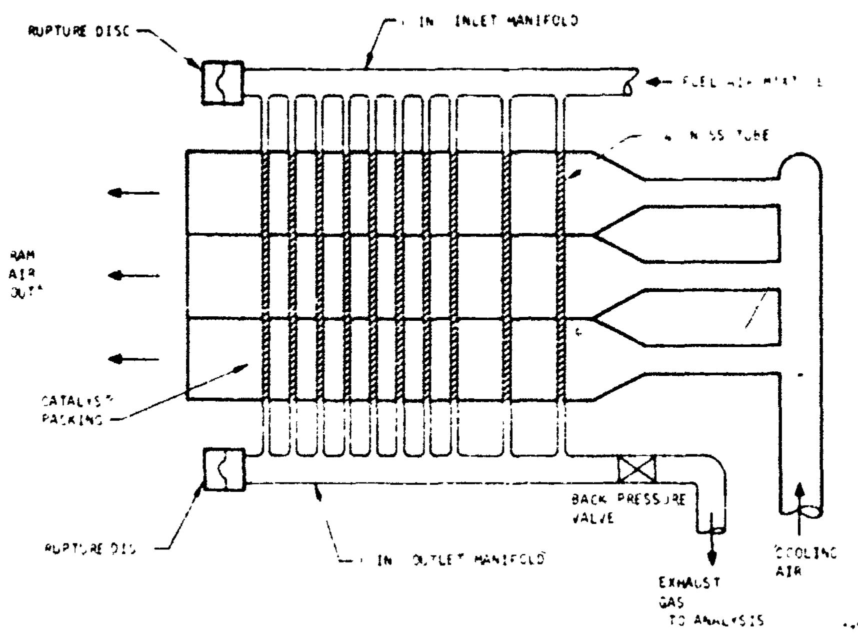


Figure 72. Catalytic Reactor Tube Bundle Schematic

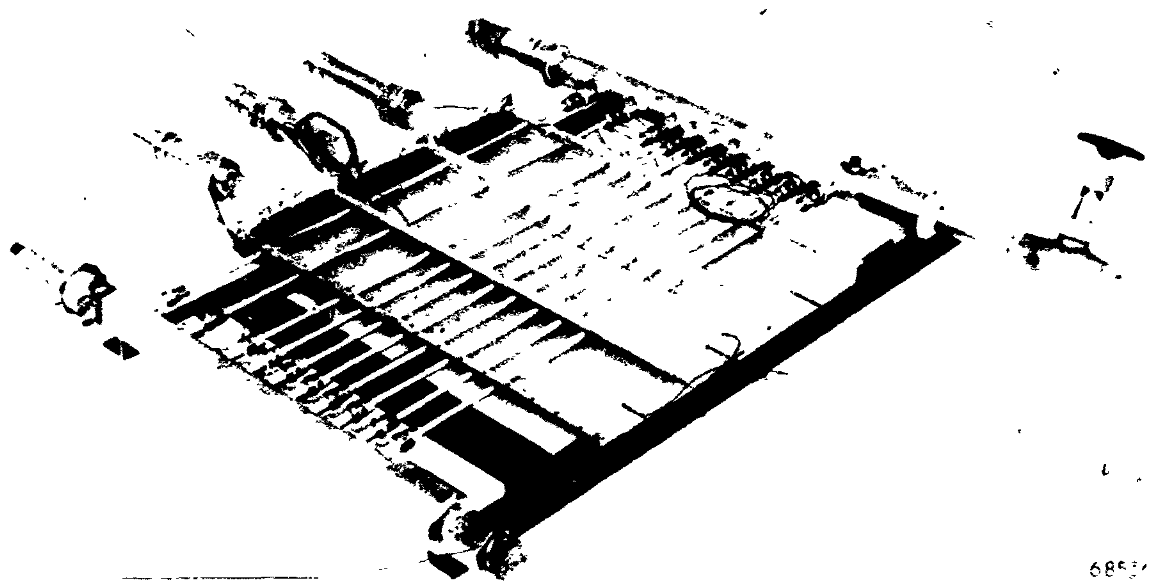


Figure 73. Catalytic Reactor Tube Bundle Photograph

The arrangement allows cooling air to be distributed along the catalyst-packed portion of each tube. This facilitates determination of heat transfer data since the arrangement simulates the design configurations used by many flight-type heat exchangers. Alternatively, the cooling air flow can be discontinued and the tubes exposed to ambient (as shown in the photograph) to make the testing visually accessible. In this mode, some tube cooling is provided by radiation, however, at high throughflows, it is necessary to supply cooling air or reduce the fuel/air ratio if the tubing temperatures are to remain acceptable. Figure 73 shows the thermocouples that are spaced along the length of the first two tubes. In later testing, only the first tube was instrumented along its entire length; however, a single thermocouple was placed on each tube to indicate if reaction was occurring.

Figure 74 shows a schematic of the entire test configuration, indicating instrumentation and flow paths. Figure 75 is a photograph of the test setup. The reactor inlet air flow rate is measured by a calibrated orifice and the air is then preheated to the desired temperature. The JP-4 referee fuel is metered as a liquid into the air stream, vaporized, and mixed with air in a heated mix chamber before passing into the reactor inlet manifold. A Lapp Pulsafeeder pump is used to vary the fuel flow rate and insure the desired fuel/air ratio is maintained. (Initial attempts to use a needle valve to meter the fuel were unsuccessful since the very low flow rate could not be accurately maintained.) The reactor combustion products are cooled in a water cooler and analyzed as required. Additional analyses in detail have been made by collecting gas samples and analyzing them in a laboratory. A valve on the reactor discharge line can be used to simulate reactor operation under pressure greater than atmospheric.

CATALYST STUDIES

Summary

The catalytic reactor test equipment was used to evaluate the performance potential of the 38 different catalysts listed in Table 25. Only a few of the catalysts cause reaction of the fuel/air mixture. No single catalyst is completely satisfactory for the fuel tank inerting applications; however, there are two combinations of catalysts that are acceptable. Either the American Cyanamid Code A catalyst combined with platinum, or the Grace 908 catalyst used in conjunction with platinum would be acceptable for this application. Further work with the preferred catalyst combination, the Code A/platinum mixture, will be required to improve stability, pressure drop characteristics, and life expectancy. All three are thought to be obtainable by changing the catalyst carrier.

Precious Metal Catalysts

Palladium (ESPI PGC 305) and platinum (ESPI PGC 315) both 0.5 percent on 1/8 in. alumina pellets, were initially found to provide the lowest light-off temperature and the highest degree of reliability. The platinum catalyst (ESPI PGC 315) was arbitrarily selected as a qualitative reference. Platinum caused fuel/air reaction at inlet temperatures as low as 400°F and it could be

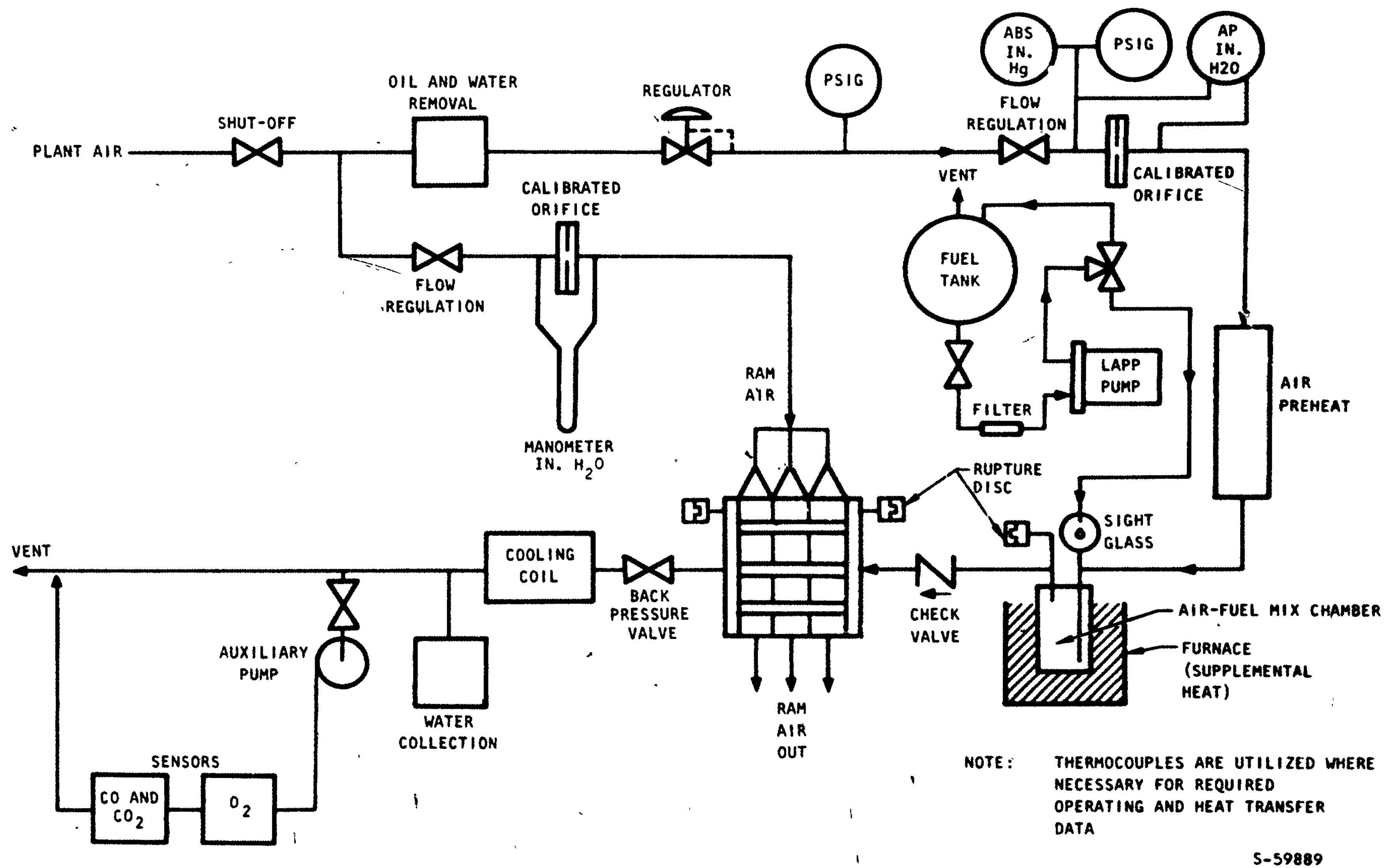


Figure 74. Catalytic Reactor Test Equipment Schematic

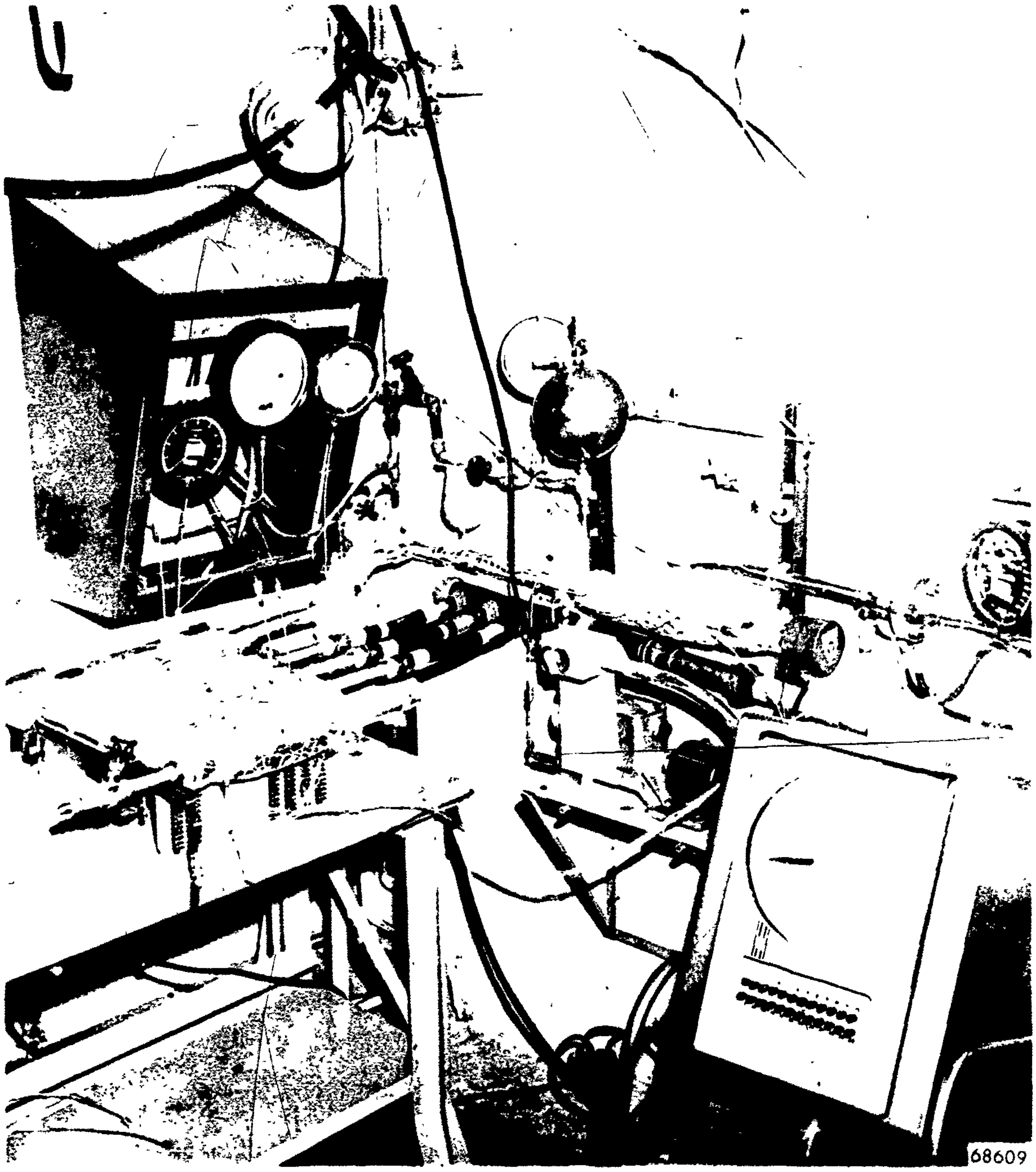


Figure 75. Catalytic Reactor Test Equipment Photograph

TABLE 25

OXIDATION CATALYSTS TESTED IN CATALYTIC REACTOR TEST UNIT

Type	Remarks
HOUDRY 8	
Type K	Slight activity
Type 541CXI-XI	No ignition
Type 133CP2-3XI	Pellent disintegrated in tube
Type 1120JXI-1XI	No ignition
Experimental nickel	Ignited with Pt igniter; quick burnout
ENGELHARD	
Platinum (0.5% on Alumina-Sulfided - C5506)	Good ignition and stability (comparable to ESPI P6C315)
Ruthenium (0.5% on Alumina)	No ignition
GIRDLER	
T-366 (Copper Oxide on Kieselguhr)	Some activity
T-1065 (Palladium and Chromia on Alumina)	Active but tended to decay
G-3A (Chromium Promoted Iron Oxide)	No ignition
G-67RS (Reduced and Stabilized Cobalt)	Ignited - slow burnout
G-61RS (Cobalt on Kieselguhr)	Ignited - slow burnout
HARSHAW	
Cu1700T (79% Copper Oxide)	No ignition
Cu0402T (Copper Chromite)	No ignition
Mn-0201T (Manganese	Ignited with Pt } Should be reinvestigated
Ag-0107E (Silver)	Ignited with Pt } Should be reinvestigated
Ni-0104T (Nickel)	Hard to light - slow burnout
GRACE (Davison Chemical Co.)	
SMR 7-1744 (10% CuO-0.04% Pd)	No ignition
903-08-5X-1949 (Grade 903)	No ignition
SMR-7-3277 (Grade 908-CuO, Mno, trace Pd)	Ignited with Pt - tended to burn out but could be reactivated. Additional tests.

TABLE 25 (Continued)

Type	Remarks
AMERICAN CYANAMID	
Code A	High pressure drop - Ignites with Pt but catalyst carrier deteriorates - additional tests
UNIVERSAL OIL PRODUCTS	
O_x A (1/16-in. Pellents) } Arbitrary designation	High pressure drop - igniter
O_x B (3/32-in. Pellets) } Arbitrary designation	Low ignition temp - possible burnout. (Above should be reinvestigated)
ELECTRONIC SPACE PRODUCTS (ESPI)	
PGC 305 (Palladium, 0.5% on Alumina)	Good ignition - satisfactory
PGC 315 (Platinum, 0.5% on Alumina)	Good ignition - primary standard
K2893C (Iridium Oxide Powder)	No ignition
K4550B (Rhodium Sesquioxide Powder)	No ignition
K-1136J (Cerium Oxide Powder, 95%)	No ignition
MISCELLANEOUS	
Rare Earths (Mixtures of Oxides of Cerium, Neodymium, Praseodidymium and Terbium)	No ignition
Silver Oxide (MCB Reagent Powder)	Slight activity
Copper Chromate (Alfa, Catalyst Grade)	No ignition
Copper Chromite (Powder)	No ignition
Cobalt Oxide (CO_3O_4-Spinel)	No ignition
Nickel Ferrite ($NiFe_2O_4$-Spinel	No ignition
Ferric Oxide (Fe2 03)	No ignition
Cobalt Shot } as Metals	No ignition
Nickel Shot } as Metals	No ignition
Copper (granulars) } as Metals	No ignition
NOTE: Powders were tested on Carborundum Catalyst Carrier MMT (1/8 in. Mullite Cylinders) by rolling and screening to remove excess powder.	

re-ignited repeatedly with a high degree of reliability; however, it did not cause complete reaction to take place. The degree of reaction or the amount of oxygen left in the exhaust gas, appeared to be a function of the equilibrium temperature at which the catalyst was operated. This could be controlled by the method used for cooling the tubes, i.e., depth and type of insulation, radiation, ram air flow, etc. It is probable that some coking takes place over the platinum catalyst and the carbon in the JP-4 is not completely reacted with the oxygen in the air.

Other platinum catalysts that have been found to be active are the Engelhard (0.5 percent on alumina, sulfided) and the Universal Oil Products (OXA and OXB) catalysts. (The UOP catalysts are coded OX1 and OX2 by UOP but were not properly defined when shipped, so arbitrary letters were assigned.) OXA (1.16 in. pellets) could not be properly evaluated because the pellet size caused excessive pressure drop and very little flow could be obtained.

Except for platinum and palladium, no other precious metal catalysts (i.e., rhodium, ruthenium, or iridium) were found to provide catalytic activity under the conditions employed. Girdler T-1065 (palladium and chromia) was active but its activity tended to decay with time. Reduced cobalt (Girdler G-67RS and Girdler G-61R5) and nickel (Houdry experimental nickel) catalysts were active only for brief periods and then burned out, probably by oxidation of the cobalt or nickel to an inactive oxide state.

Metal Oxide Catalysts

Catalysts having manganese, copper, or silver oxides or compounds appeared to be active although such activity was often erratic. For Code A (American Cyanamid) catalyst, analyzed as a copper compound, ignition took place in different tubes at different locations and, within a given tube, at different times. The result was a series of hot spots for which it was necessary to supply ram air for cooling. This caused the remainder of the tubes to be reduced in temperature below the point at which ignition could occur. Failure to cool the hot spots caused some catalyst carrier pellents (molecular sieves) to sinter and fuse together, plugging the tube and necessitating removal. Temperature rise could be very rapid with the maximum temperature exceeding 2000°F in one instance before ram air cooling could bring the reaction under control. Figure 76 shows the variation in tube temperatures at various times for a tube packed with American Cyanamid Code A catalyst.

1. Active Catalysts

In addition to the American Cyanamid Code A catalyst, the Grace Grade 908 (a mixture of CuO and MnO2), and Harshaw Catalysts Mn-0201T and Ag-0107E were also active if platinum was used as an igniter. Note that the above oxides (copper, silver, manganese) are those used in Hopcalite, a catalyst used in gas masks for the low temperature oxidation of carbon monoxide. This group of active catalysts, all having related chemical compositions, indicates that a combination of platinum with such oxides as copper, silver and/or manganese would probably provide the desired combination of properties.

2. Grace Grade 908 Catalyst Tests

Some additional work was undertaken with Grade 908 (Grace). This catalyst would ignite, then burn out, but could be re-ignited by briefly blowing air over the catalyst before again introducing the fuel/air mixture. It appears that the catalyst converts to an inactive state as catalysis occurs but that this state can be reactivated by subsequent oxidation in an air stream. In one test a tube containing Grade 908 was stabilized with a platinum pellet at 2-in. intervals and performance was highly satisfactory for a period of some hours. Unfortunately this test could not be repeated when a series of tubes were so treated. Tests with Grade 908 with only platinum as an igniter also were not satisfactory since the catalyst would burn out leaving only ~~the~~ platinum portion igniter. Modification of Grade 908 might result in a satisfactory final catalyst.

3. American Cyanamid Code A Catalyst Tests

Code A (American Cyanamid) and platinum mixtures have been tested to ascertain if the erratic behavior of Code A can be corrected. It appears that the chief fault with Code A is its carrier. The catalyst composition appears to be suitable, if augmented with platinum, to provide a final catalyst that would incorporate the desired properties.

The Code A catalyst has apparently been applied to a porous molecular sieve structure. It is possible this porosity is a necessary requirement for proper functioning but data indicate catalytic activity apparently occurs even after this porosity has been reduced or eliminated by prolonged operation at temperatures in excess of 1500°F. Thus applying the catalyst to a different carrier, i.e., 1/8-in. alumina pellets, should not be detrimental. At present the catalyst is highly concentrated on small pellets providing a high pressure drop and a large surface area for rapid reaction in a reduced volume, i.e. all the requirements for a hot spot to develop. Dilution of the catalyst is required if the heat of reaction is to be spread out over a sufficient surface for controlled removal. By using a large catalyst carrier with less catalytic surface area per unit volume, such dilution is automatic and all of the tube length is employed. In any event the possibility of plugging of the tubes by shrinkage and sintering such as presently occurs with the molecular sieve type of catalyst carrier, is avoided.

Various mixtures of Code A with platinum have been tested. Initially tubes employing a 4-in. bed of platinum pellets ahead of an 8-in. bed of Code A were used. The platinum supplied partial reaction. A hot spot would develop at the platinum-Code A interface that would move through the Code A bed to the end of the tube and then the Code A catalyst would go out and usually cease to supply any further combustion. Occasionally the catalyst would re-ignite and repeat the process (as shown in Figure 76 for an all-Code A packed tube). Code A was similarly tested with only one or two platinum pellets to supply initial ignition but essentially the same results were obtained, i.e., ignition would occur but a hot spot would move down the bed and eventually the tube would cease to support reaction. In a third test platinum pellets were used at approximately 2-in. intervals through the Code A bed. In this test, a stable

arrangement was obtained. With this arrangement it was possible to get all tubes to ignite and burn in approximately the upper 4-in. of the catalyst bed. The hot zone was relatively stable and reaction appeared fairly complete. When the hot zone was cooled by external sources, however, the zone would start to move down the tube and eventually the tube would go out. Apparently radiation from surrounding tubes was effective in maintaining stable operation since the end tubes were the least stable and would usually quit first. It was necessary to supply some insulation to avoid exposure to ambient air. The hot zone temperatures were usually in excess of 1700°F, with the bulk of the heat apparently being removed by radiation; however, several hours of operation could be obtained.

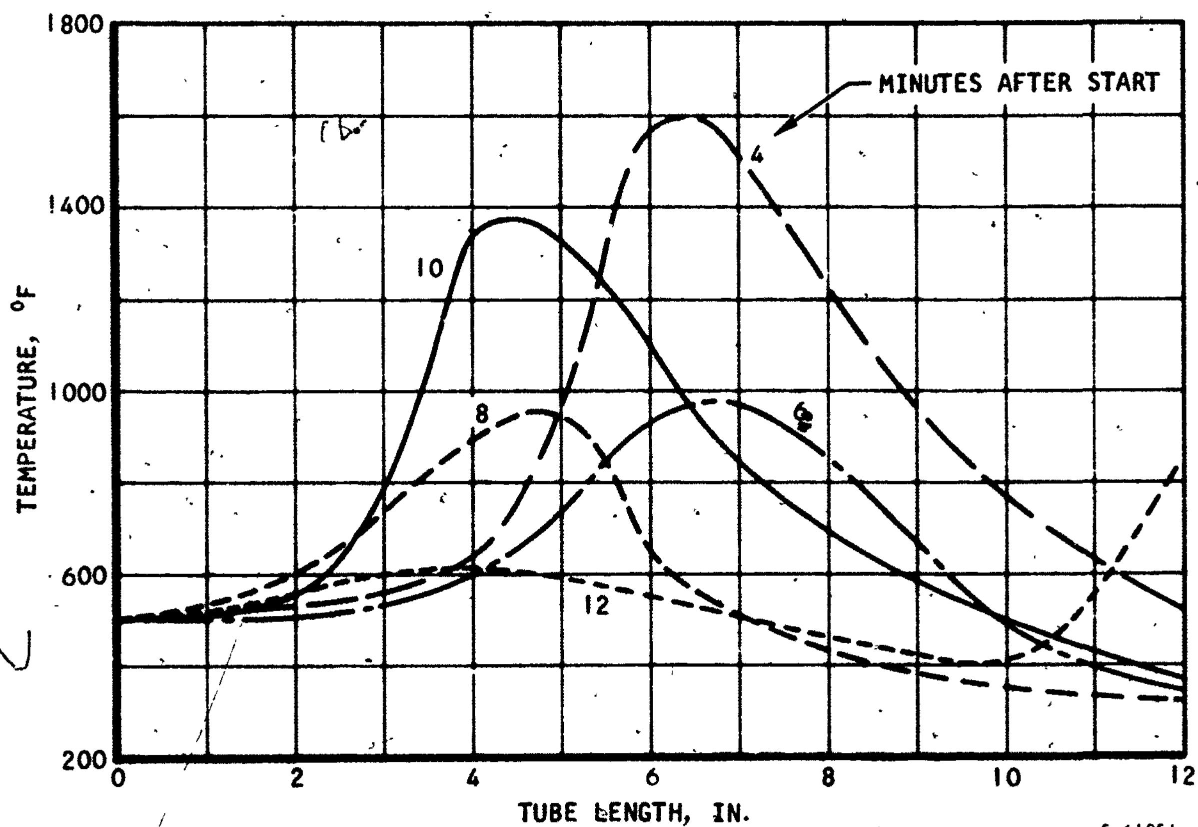


Figure 76. Tube Wall Temperature Variation for Typical American Cyanamid Code A Catalyst

Inert Gas Composition

1. Gas Analyses

Tables 26, 27, 28, and 29 present the findings of gas analyses conducted by an independent testing laboratory on gas samples of two types: 2 samples in which the catalyst was platinum (Tables 26 and 27) and two samples in which the catalyst was Code A (Tables 28 and 29). The data indicate that the fuel-air reaction with platinum as the catalyst is incomplete with a conversion efficiency of about 70 percent. With Code A, essentially 100 percent conversion to inert is obtained. Thus, the inert gas composition with Code A catalyst is almost identical to that obtained by theory--such as displayed in Figure 77.

2. Condensate Acidity

The acidity of the condensate formed in the regenerator of the proposed inerting system will determine what materials are required in the regenerator. Additionally, the acidity will provide an indication of the probable effect of introducing the inert gas (which will still contain some water vapor and some sulphur dioxide) into the fuel tanks.

Acidity was measured by condensing the catalytic reactor exhaust gas moisture at two different temperatures. The first condensate was obtained at a temperature of about 60°F using water as the heat sink. The exhaust flow was then passed through a liquid nitrogen trap that removed all the remaining moisture from the gas flow. When the first condenser was made of copper, the moisture obtained from both the high and low temperature traps had a pH of about 5-6, equivalent to that of distilled water. However, the color of the condensate (bluish-green) indicated that the sulphur dioxide was probably reacting with the copper condenser to form copper sulphate. When the condenser and all exhaust line materials were replaced with stainless steel components, the exhaust gas condensate from both the high and low temperature traps had a pH of about 3. Therefore, it can be concluded that the inerting system regenerator and all gas lines must be made of stainless steel. Additionally, it appears that some acidity will be introduced into the fuel tanks unless some special scrubbing provisions are provided for removal of the sulphur dioxide.

Although the test fuel used in the catalytic reactor test bed had a high sulphur content (0.15 percent), the lower content normally obtained will not greatly alter the acidity of the condensate.

Catalyst Bed Pressure Drop

The catalyst bed pressure drop will have an influence on the overall inerting system performance since this pressure drop reduces the pressure head available for expansion through the cooling turbine. Catalyst bed pressure drop has been determined by measuring the pressure drop through a 12 in. length of catalyst (cylindrical alumina pellets, 0.125 in. diameter by 0.125 in. long) packed in a typical reactor tube (stainless steel,

TABLE 26

PLATINUM CATALYST EXHAUST GAS ANALYSIS: SAMPLE I

DATE 7-24-70 F/A RATIO 0.058
CATALYST: Platinum ESPI PGC 315

Constituent	Analysis MOL Percent Wet	Analysis MOL Percent Dry	Equivalent F/A Ratio	Percent Reaction	Remarks
Argon } Inert	0.92	81.70	0.0320	55	Theoretical "Dry" analysis is 84.05 percent for 100 percent reaction. Analysis is consistent with high residual O_2 content.
Nitrogen } Inert	80.57				
Oxygen	9.90	9.93	0.0365	63	Theoretical of 3.2 percent. O_2 meter indicated 9.2 percent during run
Carbon Dioxide	7.59	8.15	0.0375	65	Theoretical of 12.7 percent. Analysis is consistent with high residual O_2 content
Carbon Monoxide	0.44				
Water	0.26	0.00	-	-	Water vapor should more nearly approximate 2.6 percent if saturated
Sulfur Dioxide	0.00	0.00	-	-	
Nitric Oxide	87 PPM	-	-	-	
Hydrocarbons as Butene-M.W. 56.10					0.21 MOL percent hydrocarbon corresponds to 0.40 wt percent. M.W. of exhaust gas = 29.79 or a residual F/A ratio of 0.004 indicating 7 percent unburned and uncondensed hydrocarbons in the exhaust
Hydrocarbons as Butane-M.W. 58.12					
Methane M.W. 16.04	-				
Ethane M.W. 30.07	-				
Total	99.99				

TABLE 27

PLATINUM CATALYST EXHAUST GAS ANALYSIS: SAMPLE 5

DATE 7-24-70 F/A RATIO 0.050
CATALYST Platinum ESPI PGC 315

Constituent	Analysis MOL Percent Wet	Analysis MOL Percent Dry	Equivalent F/A Ratio	Percent Reaction	Remarks
Argon } Inert	0.91	81.94	0.0350	70	Theoretical Dry analysis is 83.3 percent for 100 percent reaction. Analysis is consistent for high residual O_2 content
Nitrogen } Inert	80.87				
Oxygen	10.57	10.59	0.0345	69	Theoretical of 5.8 percent. O_2 meter indicated 9.5 percent during the run
Carbon Dioxide	7.05	7.27	0.0335	67	Theoretical of 10.9 percent. Analysis is consistent with high residual O_2 content
Carbon Monoxide	0.21				
Water	0.20	0.00	-	-	Water vapor should approximate 2.6 percent if saturated
Sulfur Dioxide	0.00	0.00	-	-	
Nitric Oxide	96 PPM	-	-	-	
Hydrocarbons as Butene-M.W. 56.10	0.05				0.18 MOL percent hydrocarbon corresponds to 0.35 wt percent. M.W. of exhaust gas = 29.74 theory or a residual F/A ratio of 0.0035 indicating 7 percent unburned and uncondensed hydrocarbons in the exhaust
Hydrocarbons as Butane-M.W. 16.04	0.13				
Methane M.W. 16.04	-				
Ethane M.W. 30.07	--				
Total	99.99				

TABLE 28

CODE A CATALYST EXHAUST GAS ANALYSIS: SAMPLE 1

DATE 10-29-70 F/A RATIO 0.050
CATALYST: Code A with Platinum Pellet at 2 in. Intervals

Constituent		Analysis MOL Percent: Wet	Analysis MOL Percent: Dry	Equivalent F/A Ratio	Percent Reaction	Remarks
Argon	Inert	1.08	81.19	0.026	52	Theoretical "dry" analysis is 83.3 percent. Low "inert" analysis offset by high CO_2 content
Nitrogen		80.11				
Oxygen		5.69	5.69	0.050	100	Corresponds to O_2 meter during run
Carbon Dioxide		12.98	13.01	0.059	118	Theoretical "dry" analysis is 10.9 percent. See low "inert" analysis
Carbon Monoxide		0.03				
Water		0.00	[illegible]	-	-	Absence of water vapor cannot be explained
Sulfur Dioxide		[illegible]	[illegible]	-	-	
Nitric Oxide		[illegible] PPM	-	[illegible]	[illegible]	
Hydrocarbons as Butene-M.W. [illegible]		[illegible]				0.1 MOL percent hydrocarbons corresponds to 0.0875 wt percent (M.W. of exhaust gas is 29.74 theory) or a residual F/A ratio approximating 0.0009 indicating 2 percent unburned and uncondensed hydrocarbons in the exhaust
Hydrocarbons as Butane-M.W. 58.12		[illegible]				
Methane M.W. 16.04		[illegible]				
Ethane M.W. 30.07		[illegible]				
Total		99.99				

TABLE 29

CODE A CATALYST EXHAUST GAS ANALYSIS: SAMPLE 2

DATE 10-29-70 F/A RATIO 0.050
CATALYST: Code A with Platinum Pellet at 2 in. Intervals

Constituent		Analysis MOL Percent: Wet	Analysis MOL Percent: Dry	Equivalent F/A Ratio	Percent Reaction	Remarks
[illegible]	Inert	1.08	81.04	0.024	48	Theoretical "dry" analysis is 83.3 percent. Low "inert" analysis offset by high CO_2 content
[illegible]		79.96				
[illegible]		5.69	5.69	0.050	100	Corresponds to O_2 meter during run
[illegible] Dioxide		13.14	13.16	0.060	120	Theoretical "dry" analysis is 10.9 percent. See low "inert" analysis
[illegible] Monoxide		0.02				
Water		0.00	0.00	-	-	Absence of water vapor cannot be explained
Sulfur Dioxide		0.00	0.00	-	-	
Nitric Oxide		69 PPM	[illegible]	[illegible]	[illegible]	
Hydrocarbons as Butene-M.W. 56.10		0.01				0.1 MOL percent hydrocarbons corresponds to 0.0875 wt percent (M.W. of exhaust gas = 29.74 theory) or a residual F/A ratio approximating 0.0009 indicating 2 percent unburned and uncondensed hydrocarbons in the exhaust
Hydrocarbons as Butane-M.W. 58.12		0.01				
Methane M.W. 16.04		0.07				
Ethane M.W. 30.07		0.01				
Total		99.99				

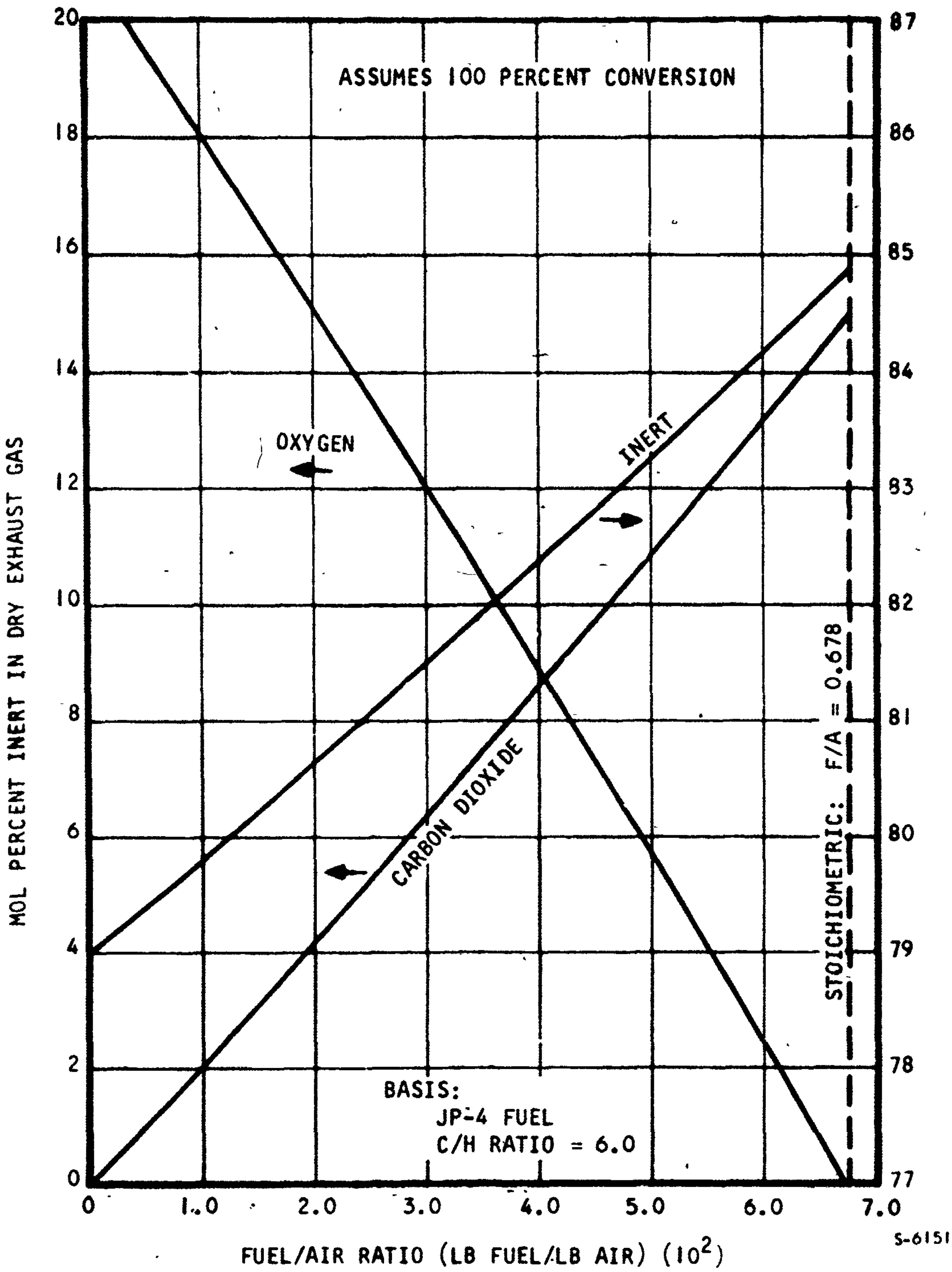


Figure 77. Variation in Composition of Dry Exhaust Gas with Fuel/Air Ratio

0.25 in. OD, 0.010 in. wall). Figure 78 shows the corrected pressure loss as a function of the flow through the tube. From these data, the Z factor for the tube is about 1000 psi per (lb/min)^2, where Z is equal to corrected pressure drop ($\sigma\Delta P$) divided by the square of the flow rate.

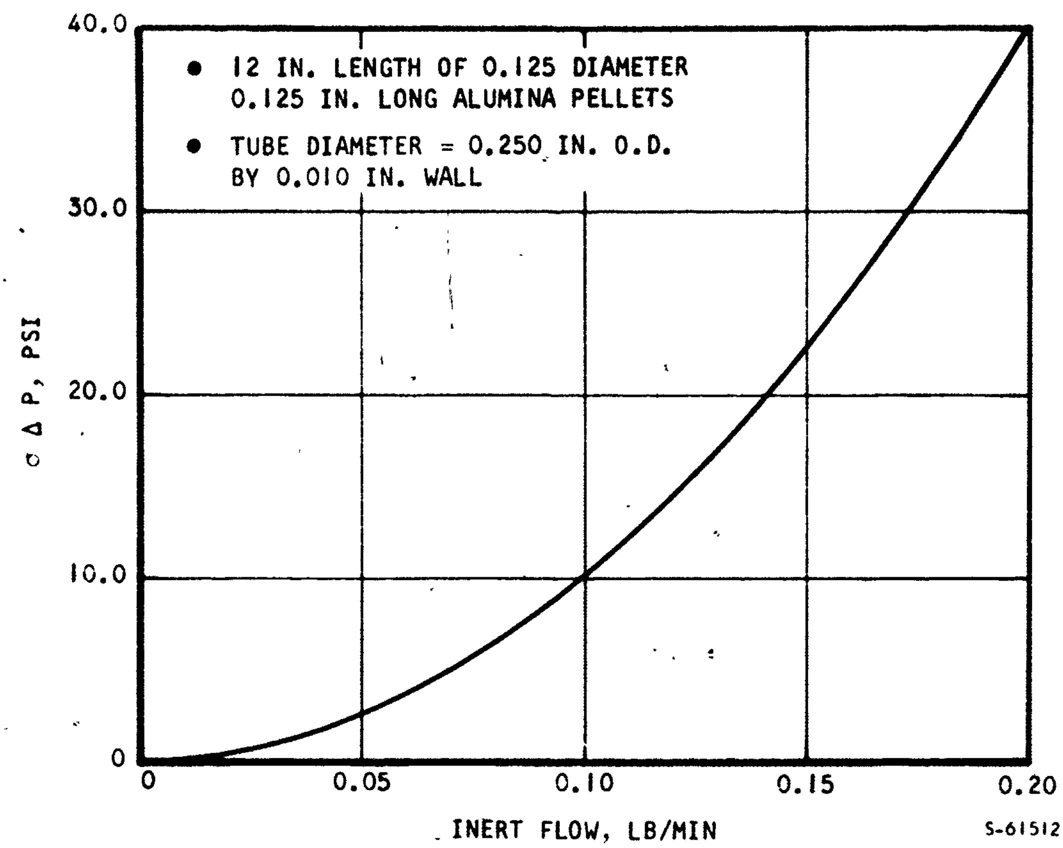


Figure 78. Catalyst Pressure Drop Data

Conclusions

The catalyst studies have resulted in the following conclusions:

- Ignition can be obtained with inlet temperatures between 400 to 450°F using a platinum catalyst as an igniter
- The low reaction efficiency obtained with platinum necessitates that it be combined with another catalyst to obtain satisfactory performance

- A mixture of American Cyanamid Code A catalyst and platinum appears satisfactory for the inerting system application, particularly if the Code A catalyst is coated onto alumina pellets instead of molecular sieve

HEAT TRANSFER STUDIES

Initial Studies

Prior to selection of the recommended Code A/platinum catalyst mixture, heat transfer studies with tubes filled only with Code A catalyst and tubes filled only with platinum were performed. Table 30 summarizes these tests and Figure 79 shows typical steady-state temperature distributions along the reactor tubing for a tube packed with platinum catalyst. The data

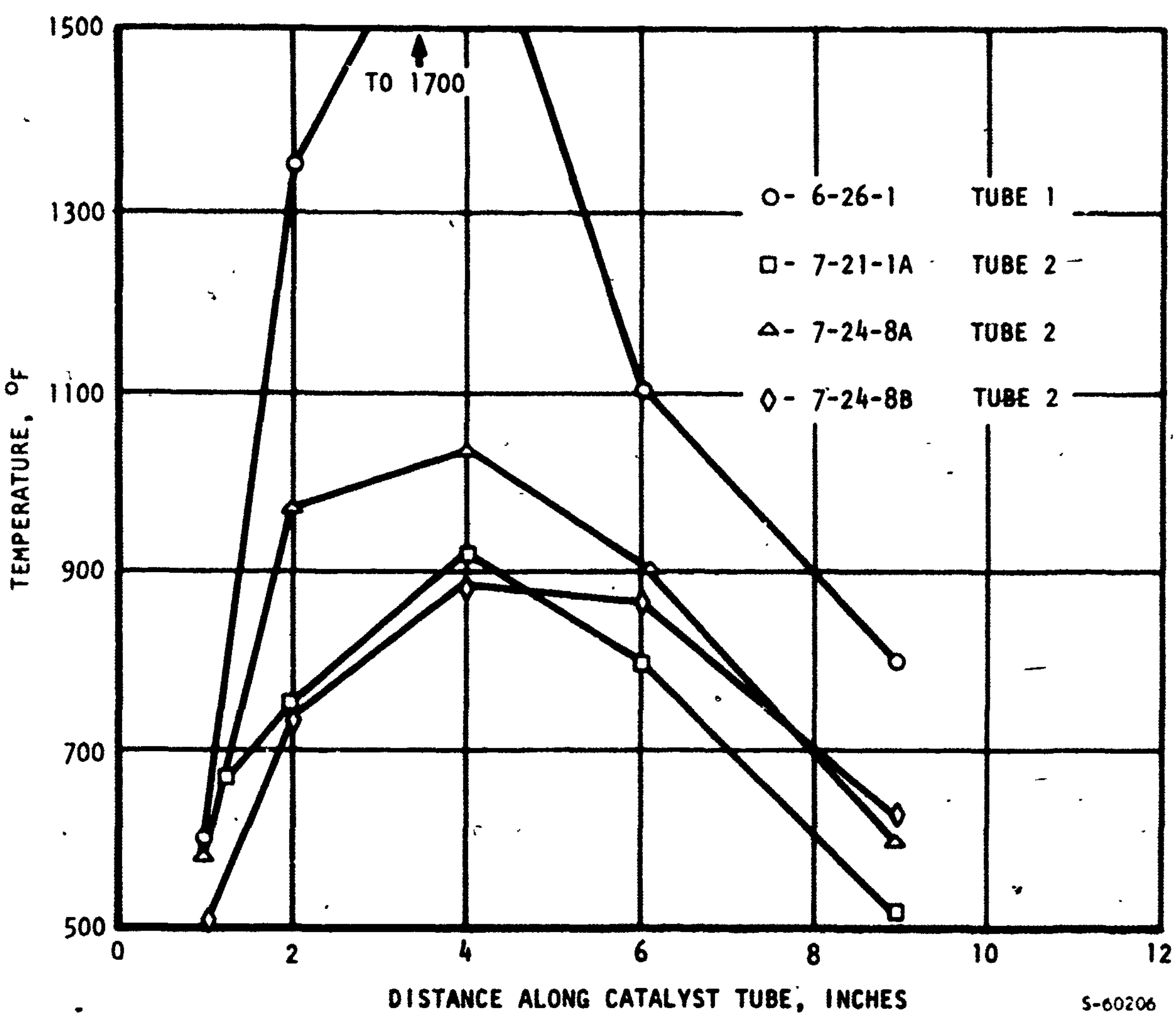


Figure 79. Catalytic Reactor Tube Temperature Profiles

TABLE 30

INERT GAS CATALYTIC REACTOR TEST DATA SUMMARY

Catalyst	Date	Run No		Steady State Time Min	Flow Rates: Fuel cc/Min	Flow Rates: Bleed Air lb/hr	Flow Rates: Ram Air lb/hr	Ratios: Fuel/Bleed	Ratios: Ram/Bleed	O_2 Content percent: Theory	O_2 Content percent: Measured	Remarks
Code A Ca[illegible]	5-[illegible]	1		8	2.5	6.0	-	0.04	-	-	-	Ram air flow not measured.
		Above was initial run--fairly steady state--tube temperatures 600-1200°F Not all data obtained										
	6-18	1		None	3.15	6.0	Variable	0.053	Variable	-	-	Unable to achieve uniform ignition
	6-26	1		6*	2.6	5.0 to 6.2		0.042 to 0.052	0	6.0	3.7	*Not at steady state conditions
		For above run on 6-26 a sparkplug was used for preignition of the fuel/air mixture so as to maintain catalytic activity in tubes										
Pla[illegible]	7-21	1A	Continuous	13	2.20	5.80	28.5	0.038	4.9	9.5	12.2	No decline in efficiency was noted
	7-21	1B		5	[illegible]	[illegible]	32.0	0.046	5.5	7.0	10.5	pH of condensed water 28cc 5.0
	7-23	1A	Continuous	5	3.25	6.0	26.0	0.054	4.3	4.5	10.3	-
	7-23	1B		[illegible]	3.50	6	26.0	0.058	4.3	[illegible].2	10.0	-
	7-23	1C		7	3.75	6.0	26.0	0.0625	4.3	1.8	13.2	Tubes went out
	7-23	2A	Continuous	16	3.0	6.0	27.0	0.050	4.5	5.8	9.9	-
	7-23	2B			3.[illegible]	6.[illegible]	22.0	0.050	3.7	5.8	10.0	-
	7-23	2C		6	3.0	6.0	22.0	0.050	3.7	5.8	13.5	Dry ice trap backpressure caused tube flameout
	7-24	1		20	3.5	6.0	19.0	0.058	3.2	3.2	9.2	Slight reduction in efficiency toward end of run
	7-24	2A	Continuous	7	3.[illegible]	7.0	26.0	0.056	3.7	3.8	9.5	Combustion efficiency started to decrease after six minutes
	7-24	2B		5	3.9	7.0	19.0	0.056	2.7	3.8	15.0	Decline in combustion efficiency
	7-24	3		8	3.6	6.6	[illegible] 8.0	0.055	[illegible].2	4.1	13.0	Poor combustion--tubes ignited at bottom exit only
	7-24	4A	Continuous	7	2.8	5.0	19.0	0.056	3.8	3.8	9.0	-
	7-24	4B		3	2.8	5.0	15.0	0.056	3.0	3.8	11.0	Decline in combustion efficiency
	7-24	5A	Continuous	15	2.5	5.0	15.0	0.050	3.0	5.8	8.7	-
	7-24	5B		10	2.5	5.0	11.0	0.050	2.2	5.8	9.9	Slight decline in efficiency
	7-24	6		11	3.[illegible]	6.0	15.0	0.050	2.5	5.8	8.8	Gradual decline in combustion efficiency
	7-24	7		3	3.0	6.1	12.0	0.049	2.0	6.1	11.5	Pressure at 30 psia Precombustion in mix chamber
	7-24	8A	Continuous	26	3.0	6.1	13.0	0.049	2.1	6.1	Valve Problems	Pressure at 30 psia
	7-24	8B		13	3.4	6.1	15.0	0.056	2.5	3.8	8.4	Pressure at 30 psia No decline in activity

consistently indicate that the maximum tube temperature occurs in the initial tubing portion. Thus, the bulk of the reaction is isolated to a small fraction of the catalyst bed only. There are a number of possible explanations for this; however, the most likely is that once reaction is initiated and the temperature exceeds the fuel autoignition temperature, the reaction continues to completion. That is, at a sufficiently high temperature, the catalyst is no longer promoting the reaction; it is self-sustaining. The autoignition temperature for JP-4 is in the vicinity of 750°F and the measured temperatures at the point of maximum heat release always exceed this temperature.

The bulk of the testing tabulated in Table 26 was performed with the catalyst bed exhausting at ambient pressure. Under this condition the reaction showed marked instability with a tendency to move within the catalyst bed. Increasing the reactor operating pressure provides smoother catalysis and a lessened bed pressure drop. In the intended application, the catalyst bed will operate at pressures in excess of 2 atm, where catalysis is relatively stable.

It becomes apparent that some means of lowering the catalyst activity so that the reaction is more evenly distributed over the entire bed is essential. Consequently, the later studies were oriented towards investigation of catalyst mixtures that would still provide a high efficiency, but that would also evenly distribute the reaction.

Recommended Catalyst Studies

The recommended catalyst concept is American Cyanamid Code A catalyst coated on 0.125 in. alumina pellets with either uncoated pellets or pellets coated with platinum intersperced in the Code A pellets. Additionally, 2 or 3 platinum catalyst pellets should be located in the initial portion of the catalyst bed to insure ignition. Figure 80 shows the variation of tube temperature along the tube length for such a catalyst bed. The data were obtained without using any cooling airflow across the tubes since such a flow caused ignition instabilities, particularly in the leading tubes (which received the cooling flow at the lowest temperatures and had the smallest amount of radiation from the remaining tubes) and the trailing tubes (which had only a small amount of radiation). Thus, it appears that the reactor should be designed so that the tube portion in which the reaction is occurring is cooled with relatively warm air, such as would occur in a parallel counterflow heat exchanger.

Examination of the catalyst after several hours of testing indicated considerable shrinkage of the molecular sieve carrier. Measurement of individual pellets indicated a reduction in diameter of about 20 percent. Measurement of the overall bed showed up to 30 percent reduction in bed length. Tests with other catalysts on alumina pellets showed no shrinkage;

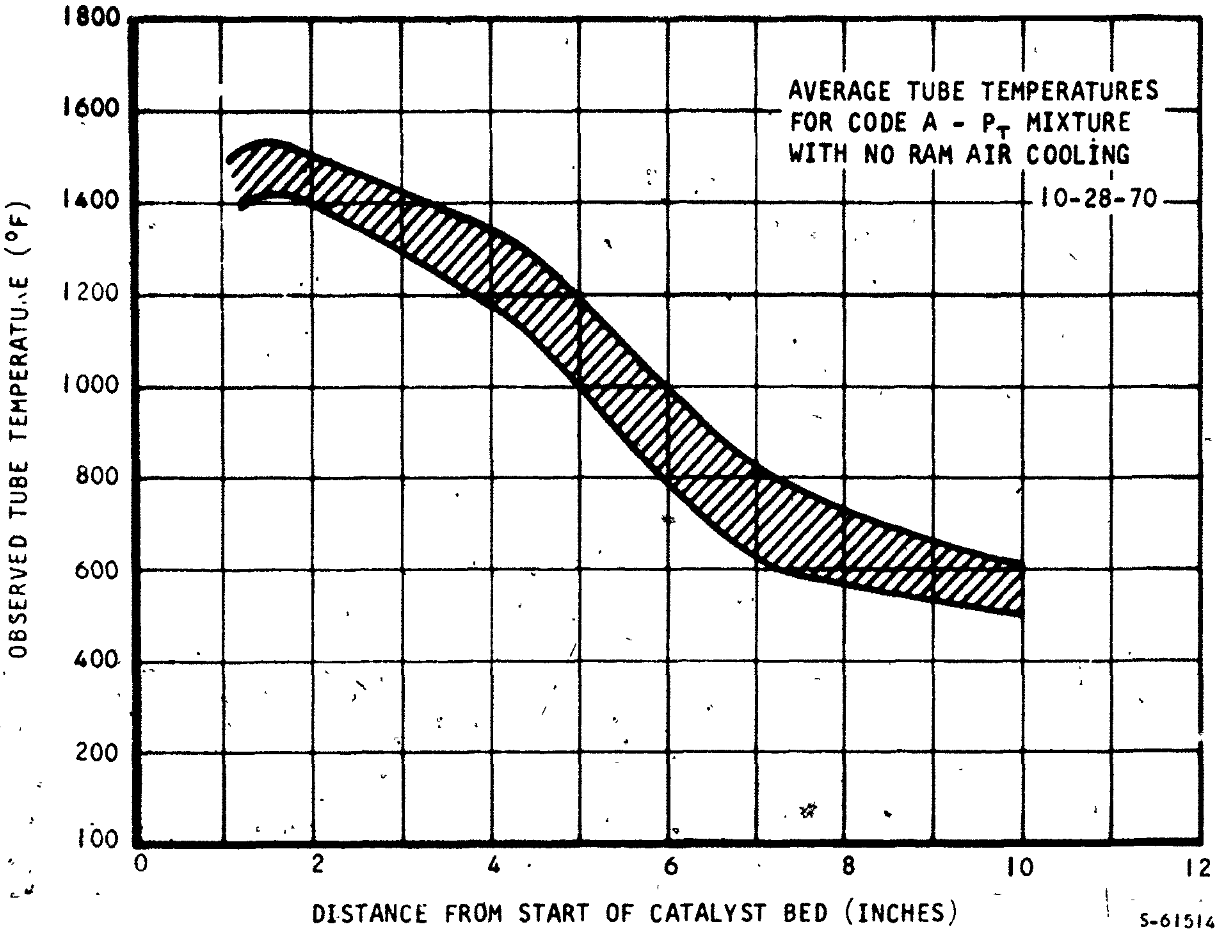


Figure 80. Recommended Catalyst Heat Transfer Data

therefore, the Code A catalyst should be coated on alumina pellets for improved performance. During the testing, the shrinkage and resultant packing of the molecular sieve caused a significant increase in the bed pressure drop. The uneven rate of deterioration in the individual tubes led to large flow variations between the tubes and hence to loss of ignition over a period of time.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The Garrett Corporation AiResearch Manufacturing Co. 9851 Sepulveda Blvd, Los Angeles, C. 'fornia	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

AIRCRAFT FUEL TANK INERTING PROGRAM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

FINAL REPORT 1 April through 31 October 1970

5. AUTHOR(S) (First name, middle initial, last name)

MacKenzie L. Hamiltor

6. REPORT DATE January 1971	7a. TOTAL NO. OF PAGES 120 + 12 front matter = 132	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO F33615-70-C-1492 b. PROJECT NO 3048 c. TASK NO. 304807 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 70-6926-1 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFAPL-TR-70-83, Volume I	

10. DISTRIBUTION STATEMENT

Each transmittal of this document outside the Department of Defense must have prior approval of the Air Force Aero Propulsion Laboratory (AFAPL/SFH), Wright Patterson AFB, Ohio 45433.

11. SUPPLEMENTARY NOTES N/A	12. SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

The Aircraft Fuel Tank Inerting Program has compared inerting system concepts and performed a preliminary design of the preferred inert gas generator (IGG) system for the B-1 aircraft. Inerting system specifications have been developed for the B-1 and F-15 aircraft. The preliminary design activity has been supported by catalyst and catalytic reactor laboratory testing. With the exception of the catalytic reactor, the inerting system components are state of the art and similar in design and function to aircraft environmental control system (ECS) components. The program compared the IGG inerting concept with the liquid nitrogen inerting method of providing inert gas to the fuel tanks. The IGG concept appears to offer both weight and operational advantages (by eliminating the requirement for supply of cryogenic nitrogen). It uses aircraft engine fuel and bleed air as the inert gas source by catalytic reaction to remove the oxygen from the bleed air. Ram air and fuel are used as heat sinks for inert gas cooling and moisture removal. Low temperature moisture removal is provided by a cooling turbine (similar to those used for aircraft environmental control) to reduce the moisture content to levels below those obtained in service with fuel tanks vented to ambience. (U)

Each transmittal of this abstract outside the Department of Defense must have prior approval of the Air Force Aero Propulsion Laboratory (AFAPL/SFH), Wright Patterson AFB, Ohio 45433.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aircraft Fuel Tank Inerting						
Catalytic Reactor						
Air-Cycle Refrigeration System						
Liquid Nitrogen Inerting System						
Inert Gas Generator Inerting System						